Master's thesis

Double Master's Degree in Industrial Engineering and Nuclear Engineering

Documentation, Design, Simulation and Implementation of an Electron Cyclotron (EC) control system for ITER

REPORT

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Abstract

The *ITER* project was created with the goal of showing the world that fusion energy is possible and can be a major step towards having a whole new kind of commercial reactors in the energy sector. Fusion energy is obtained from the fusion reactions that take place into a plasma that is at more than 150 million degrees Celsius, which is approximately 10 times the temperature at the core of the sun.

How can such a high temperature be achieved? For the operation of the reactor, an external current is induced inside of the plasma. Up to more or less 1 keV (11.5 million degrees), the plasma has some resistivity, which means that there will be Ohmic heating due to that current flowing through the plasma, that can be progressively increased. But after reaching 1 keV, the plasma resistivity becomes too low to keep heating it. This makes other external heating methods essential for the operation of the reactor.

One of these external heating systems is the *Electron Cyclotron Resonance Heating* (ECRH). It consists in heating the electrons inside the plasma by means of electromagnetic waves at the resonance frequency of a given surface in the magnetic field. This radio frequency is generated in a device called *Gyrotron*. In this device, electrons are emitted from an 'electron gun' and are accelerated through a tube. These electrons oscillate in the presence of an external magnetic field, generating the electromagnetic wave that, after being adapted, will be guided inside the reactor.

The *Gyrotron* needs several auxiliary systems to operate such as power supplies, superconducting magnets and ion pumps. They have to work correctly and in the right moment, coordinated with the whole plant operation. The Electron Cyclotron Control System (or ECCS) is in charge of controlling the 24 *Gyrotrons* of the *ITER* reactor, together with the high voltage power supplies, the transmission lines and the launchers. The ECCS ensures the correct operation of the whole system and its protection.

This project will be focused on the control system of the *Gyrotron* and its auxiliaries and will be divided into different parts. The first part will be dedicated to give some background on how does a *Gyrotron* work, the physics behind it, what are its different components and how can these components be controlled. This will be essential for the next phase: the design of the control system, including all the auxiliary systems taking part in the operation of the *Gyrotron*.

Since the *Gyrotron* is an experimental and complex device, it is vital to first test the overall system in a simulation environment, to reduce the time and effort needed for the tests and validation phase. Moreover, this will reduce the risk of damaging the *Gyrotron* and its auxiliaries allowing minimizing the design and implementation errors.

This will be done creating a model on which several simulations will be run for different possible operating scenarios, operation modes, possible accidents and faults. Finally, after passing all the tests, the system will be implemented in a dedicated Electron Cyclotron (EC) *Test Facility* that was established at the SPC (Swiss Plasma Center), in Lausanne (Switzerland), for the full power testing of the real *Gyrotron*. The results obtained in the test facility will be used for the system that will be installed in the *ITER* reactor.

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Acronyms and Abbreviations

Acronym	Meaning
A	Ampere
BPS	Body Power Supply
CDCPS	Collector DC Power Supply
CFPS	Cathode Filament Power Supply
CSWPS	Collector SWeeping Power Supply
CVD	Chemical Vapor Deposition
CWS	Cooling Water System
D	Deuterium
DC	Direct Current
DEMO	DEMOnstration Power Station
ECCS	Electron Cyclotron Control System
ECRH	Electron Cyclotron Resonance Heating
EG	Electron Gun
eV	electron-volt
F4E	Fusion for Energy
GCPS	Gun Coil Power Supply
GDP	Gross Domestic Product
GUI	Graphic User Interface
h	hour
He	Helium
HMI	Human-Machine Interface
HV	High Voltage
HVPS	High Voltage Power Supply
ICF	Inertial Confinement Fusion
ICRH	Ion Cyclotron Resonance Heating
IFMIF	International Fusion Materials Irradiation Facility
IPPS	Ion Pump Power Supply
ITER	International Thermonuclear Experimental Reactor
JET	Joint European Torus
k	kilo-
L	Liter
Li	Lithium
LOC	LOCal
LP	Long Pulse
MATLAB	MATrix LABoratory
MCF	Magnetic Confinement Fusion

min	minute
MOU	Matching Optical Unit
MPS	Main Power Supply
OT	Oil Tank
PS	Power Supply
REM	REMote
RF	Radio Frequency
s	second
SCM	Superconducting Magnets
SCMCS	Superconducting Magnets Cryogenic System
SCMPS	Superconducting Magnets Power Supply
SP	Short Pulse
T	Tritium
TL	Transmission Line
V	Volt
W	Watt

Introduction

The ITER fusion nuclear reactor is a machine that needs to be at around 150 million degrees Celsius in order to produce a plasma in the conditions to generate enough fusion reactions to get a positive balance of energy. However, the reactor cannot reach that temperature by its own, which is why it is necessary to install auxiliary external heating systems. One of the main heating techniques is the Electron Cyclotron Resonance Heating system, which will heat the plasma by transferring energy to the electrons through radiofrequency (RF) waves.

These RF are generated inside a device called the Gyrotron. It is a complex system that depends on many other auxiliary subsystems to operate correctly. This means that a complex and safe control system has to be designed in order to make this system work in a coordinated way in the right time and in the right way. This control system will have to operate at two main levels:

- Control:
  - The auxiliary systems to make sure they are all operating in the necessary conditions to make the gyrotron available.
  - The use of the gyrotron depending on the state of the plasma.
  - The way the gyrotron will operate depending on the user's requirements (the way of operation is not the same if the plasma pulse is short or long).
- Machine protection system: in case of any fault, alarm, anomaly or disturbing event to bring all the systems and subsystems to safe shut-down conditions.

For this reason, before installing these components in the ITER reactor, the gyrotrons and their auxiliaries need to be tested first in a Test Facility in order to make sure that everything works in the correct way to keep the risk of a failure on any of these systems as low as possible when operating the reactor.

Objectives

The main objective of this project is to create a control system for the gyrotron in order to test its operation with all its auxiliary systems. The model has to be as close as possible to the real system, taking into account the real input/output signals of each system and subsystem so that it can be used as a test platform of the real case.

The control system has to be fast, safe and robust in order to be able to face any possible situation, malfunction or failure in any part that might occur during the operational life of the components.

If during a pulse there is a fault in any of the components, the gyrotron has to be immediately shut down in order to prevent any possible damage. The pulse will always be stopped and so will be the required auxiliary subsystems (this will depend on what and where the fault is).

Scope of the project

In order to achieve the objectives of this project, some previous actions are needed:

- To understand the behavior of the gyrotron, its operational requirements, the physics behind and its connections and interfaces with the subsystems that make it function.
- To understand the characteristics, properties and technical documentation of all the auxiliary subsystems that will allow the operation of the gyrotron.
- To study the different required modes of operation of the gyrotron in order to adapt the use and parameters of the subsystems to the expected conditions.

These will be the first steps to create a model of the control system that will allow bringing this system from the total off state of all of its components to the synchronized full operation of all of them. This control system needs to have a model for each of the subsystems involved in the gyrotron in order to coordinate and take them all into account in the operation.

After designing this complex model, which will be done by using the MATLAB/Simulink environment, it is required to find a way of having an interface as simple as possible where the user can both operate and monitor the system.

To make sure that the model works correctly and is safe in front of any kind of failure in any subsystem, some simulations of the model will be ran. A code will also be developed in order to be able to make automatic tests of the system just by giving a sequence of instructions at the input of the system and see how it behaves in order to follow it.

All these systems will be compared to the real tests performed in the Test Facility located in Lausanne to make sure that the model is also valid with the real components. This part is out of the scope of the project as all this will be performed during the summer due to delays in the delivery of some of the components. This project is then only focused on the creation of the computer model of the control system.

This work as been developed in the scope of an internship performed at Fusion for Energy (F4E), the European joint contribution to the ITER project. This 9 months internship (from October 3^{rd} 2016 to June 30^{th} 2017) in the Departments of CODAC (Control, Data Acces and Communication) and Antennas & Plasma Engineering under the supervision of Giuseppe Carannante and Mario Cavinato has been mainly focused on the development of this control system for the operation of the gyrotron.

Chapter 1

Nuclear Fusion Energy

Nuclear fusion is known as the energy produced in the stars. The reaction consists in fusing two light atomic nuclei to form a heavier nucleus, which is the origin of every known element the can be found in the universe. This is the main difference between fusion and fission nuclear reactions.

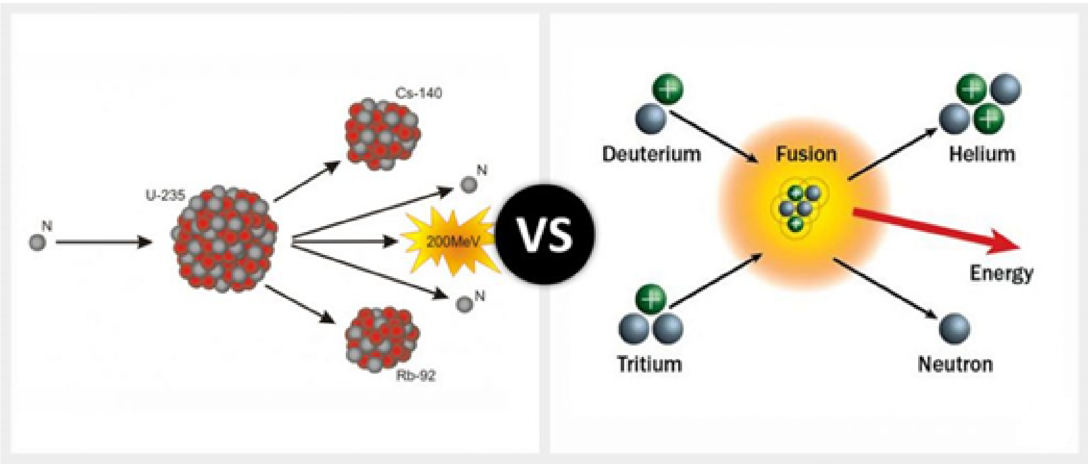

Figure 1.1: Nuclear fission vs nuclear fusion.
Source: Web picture

In fission reactions, one heavy nucleus, called the target, is hit by a neutron, called the projectile, making the atom split into two lighter elements. This reaction also releases neutrons and energy. The typical element used for fission reaction is uranium-235, which releases 200 MeV per reaction.

In both reactions, the energy is obtained from the *Mass Defect*. The mass defect of a nucleus is defined as the difference between the sum of the masses of the constituents of a nucleus (neutrons and protons) and the actual mass of the nucleus [1].

$$M'(^{A}_{Z}\mathrm{X}) < Z \cdot m_p + (A + Z) \cdot m_n \tag{1.1}$$

where:

- $M'(^{A}_{Z}\mathrm{X})$ is the nuclear mass of the nucleus of an element X with atomic number Z (number of protons) and mass number A (number of nucleons). The nuclear mass of the nucleus is defined as the atomic mass of the element $M(^{A}_{Z}\mathrm{X})$ minus the mass of the electrons $Z \cdot m_{e^-}$.
- m_p and m_n are the masses of a proton and a neutron respectively.

The mass defect Δm is defined as:

$$\Delta m = Z \cdot m_p + (A + Z) \cdot m_n - M'({}^{A}_{Z}\mathrm{X}) \tag{1.2}$$

This mass defect is associated to the energy that maintains the nucleus together through Einstein's formula $E = m \cdot c^2$ called the Binding Energy ($E_B = \Delta m \cdot c^2$). The nuclear binding energy E_B is defined as the energy required to split a nucleus into its component parts (neutrons and protons).

From this energy, the *Average Binding energy per nucleon* (E_B/A) is used to compare all the different elements. The larger this quantity is, the more difficult it is to break the nucleus in pieces.

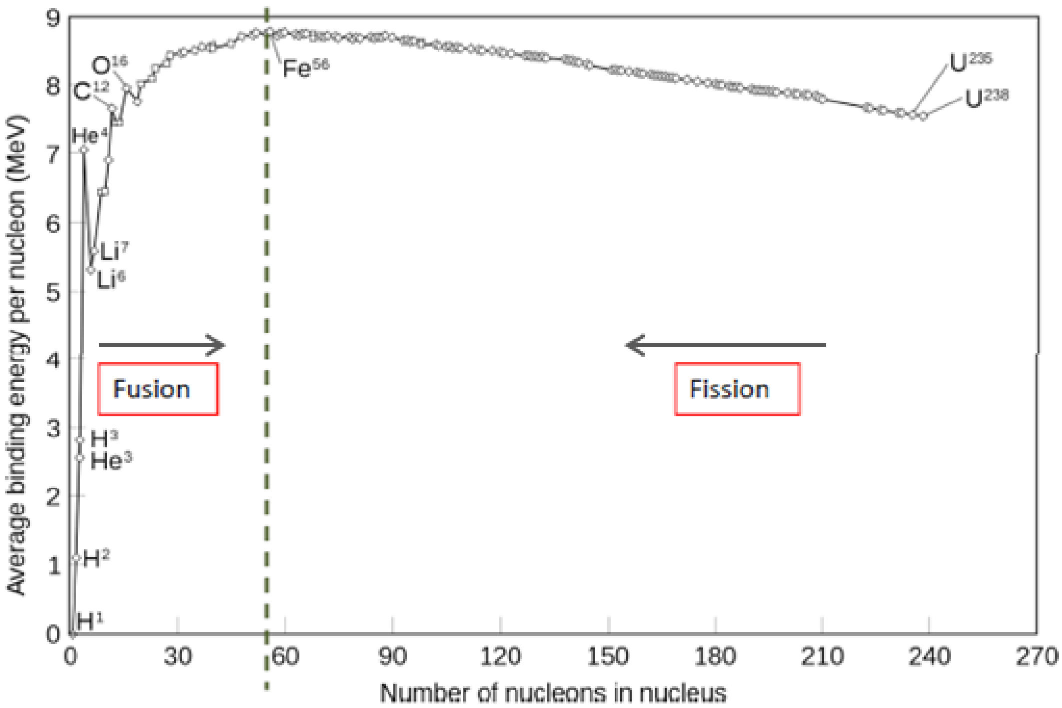

Figure 1.2: Average binding energy per nucleon.
Source: [1]

The way of obtaining energy from nuclear reactions is by going from a lower to a higher E_B/A region. In order to get energy, on the left side of the plot, it is necessary to go from a light element to a heavier one, which corresponds to a fusion reaction. However, on the right side, in order to obtain energy, it is necessary to go from a heavy element to a lighter one, which corresponds to the principle of a fission reaction. From this figure, it can be clearly seen that the energy differential that can be obtained per fusion reaction is much higher than the one from fission reactions. Actually, the energy released per fusion reaction is more or less 8 times larger than the one released in fission.

As the energy released by fusion is higher than the one released in fission, the amount of fuel needed to produce the same amount of energy will be smaller in fusion than in fission. The following figure is a comparison of the fuel consumption to produce electric power of 1000 MWe during one year (8 760 000 MWh) using 5 different types of power plants.

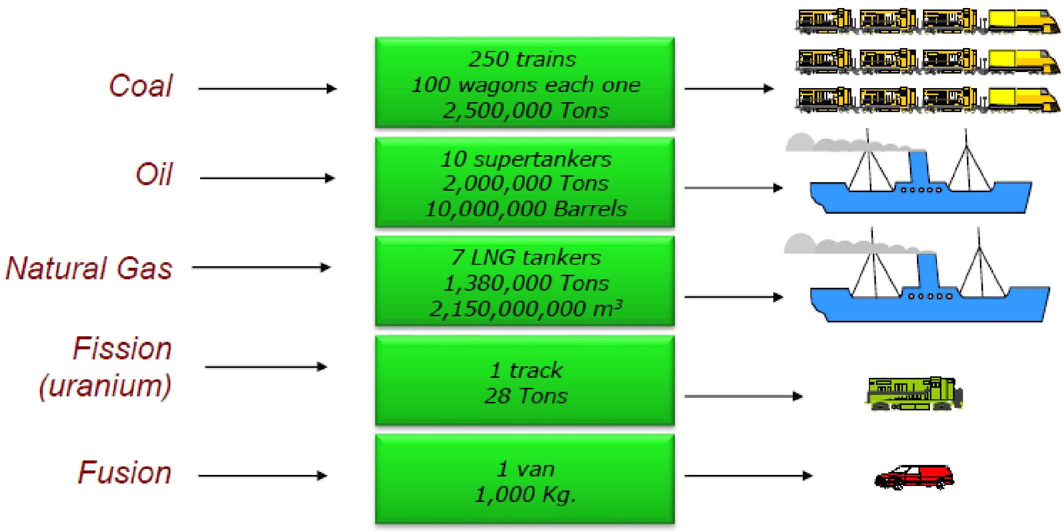

Figure 1.3: Comparison of technologies to produce 1000 MWe output power for 1 year. *Source: [2]*

1.1 The fusion reaction

Usually, the fusion reaction occurs from hydrogen isotopes (such as deuterium ^{2}H (D) and tritium ^{3}H (T)). The main reaction used for fusion is:

$$D + T \rightarrow He^4(3.5MeV) + n(14.1MeV) \tag{1.3}$$

How can the energy from fusion reactions be converted into electricity? These 14.1 MeV are the energy associated to the neutron produced from the reaction. These neutrons generated inside the reactor will hit its walls, where they will release their energy. This energy deposited on the walls of the reactor will heat water that is circulating through cooling channels right behind the wall. This water would then follow a Rankine thermal cycle that would turn the thermal energy into mechanic energy by means of a turbine that, through an electric generator would be finally turned into electrical energy.

Some information about the fuel used:

- Deuterium (D) is an isotope of water that can be found in ocean water with an abundance of 0.015%, which means there are 'limitless' resources of it. It is easy to remove from hydrogen due to the weight difference (deuterium is two times heavier than protium ^{1}H). Removing it from the water has no impact at all on the environment or the ecosystem.

- Tritium (T) is an isotope that cannot be found in the nature as it is a short life radioactive element (12 years). This means that it has to be created. This can be done inside the reactor using lithium and the neutrons produced by fusion reactions:

$$n(thermal) + Li^6 \rightarrow He^4 + T + 4.8MeV \tag{1.4}$$

$$n(fast) + Li^7 \rightarrow He^4 + T + n - 2.5MeV \tag{1.5}$$

The way of using this reaction inside the reactor is by covering the inner wall of the reactor with lithium, so that when neutrons from a previous reaction impinge on the wall, a new atom of tritium is generated. This is called a *Breeding Blanket*. There is a neutron multiplier material that would turn each neutron impinging the wall into an average of 2-3 neutrons that would then react with the lithium. This means that for each burned tritium element there are approximately between 2 and 3 new tritium atoms created, guaranteeing that the reaction will not run out of fuel and stop.

Lithium is easy to extract and obtain. Plus, there are more than 30 000 years of reserves of it in land and more than 30 million years with lithium that could be extracted from the oceans. The natural abundances are 7.4% Li^6 and 92.6% Li^7. The reaction of neutrons with Li^6 is more probable. In order to make this reaction happen it is necessary to reduce the energy of the neutrons (moderation). Moreover, the reaction with Li^7 is endothermic (it absorbs 2.5 MeV), which would cool the inside of the reactor which could stop the fusion reactions. The reaction with Li^6 is exothermic, producing 4.8 MeV that can contribute in heating the system.

The decision of producing tritium directly inside the reactor is also because, with its size, it diffuses through any material, which means it cannot be stored externally and used to feed the reaction.

The difficulties in generating and dealing with tritium might make someone wonder why is the Deuterium - Tritium (D-T) reaction the one chosen to achieve fusion power.

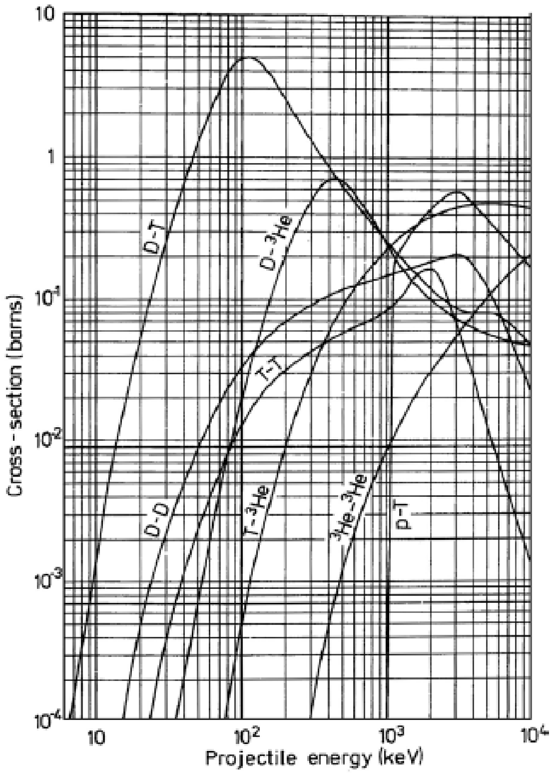

Figure 1.4: Cross-section of fusion reactions as a function of the energy of the projectile. *Source: [3]*

The plot in Figure 1.4 represents the probability of having different fusion reactions at different energies of the projectile. This energy of the projectile can be directly linked with the temperature. It can be clearly seen that the D-T reaction is the one that has the highest cross-section and a peak at a lower temperature than the other reactions, which makes it the 'easiest' reaction to achieve.

However, in the long term future, once the necessary technology, materials, expertise and knowledge will be acquired, the plan will be to move towards D-D reactions to get rid of all the difficulties related to the production and management of tritium.

$$D + D \to T(1.01MeV) + p(3.02MeV) \quad (1.6)$$

$$D + D \to He^3(0.82MeV) + n(2.45MeV) \quad (1.7)$$

In order to obtain fusion reactions, it is necessary to first have *plasma*. Plasma is the fourth fundamental state of matter (the others being solid, liquid and gas).

A plasma is an ionized gas, which means it is composed by ions and electrons. A plasma has two main characteristic properties. First, the electric charge density of the two species is so large that any substantial separation would lead to a very large restoring force. This means that the global charge densities of ions and electrons are almost equal (globally neutral). Second, a plasma can carry a current as a result of a relative drift between ions and electrons [3].

In order to fuse a nucleus of deuterium with a nucleus of tritium it is necessary to overcome the mutual repulsion due to their positive charges. As a result of that, the cross-section for fusion is small at low energies. However, this cross-section increases with energy, reaching a maximum at 100 keV and a positive energy balance is possible if the fuel particles react before they lose their energy. To know if the fusion reaction can be sustained, it is necessary to know the reaction rate. The reaction rate of D-T will depend on the density of both isotopes inside the reactor and the probability of having a reaction between them. This can be written as follows:

$$\Gamma_{DT} = n_D \cdot n_T \cdot \sigma v \qquad \left[s^{-1} \cdot m^{-3}\right] \tag{1.8}$$

where:

- Γ_{DT} is the reaction rate of the D-T reaction per volume unit.
- n_D and n_T are the density of deuterium and tritium respectively.
- σv is the reaction cross-section (probability of having the reaction). This value depends on the relative velocity v between both particles: the highest the relative velocity, the more likely it will be to make fusion occur as the particles will have more energy to counter the Coulomb repulsive forces from the nucleus. More speed means more energy, which means that, the hotter the system is, the more likely it will be to have fusion reactions.

In order to have a more generic formula, the reaction rate can reformulated as:

$$\Gamma_{DT} = n_D \cdot n_T \cdot < \sigma v > \tag{1.9}$$

being $< \sigma v >$ the reaction cross-section weighted by the velocity distribution in the plasma (which is directly related to the plasma temperature distribution).

Knowing the reaction rate, the fusion power density can be obtained as:

$$\rho_f = \Gamma_{DT} \cdot \epsilon_f = n_D \cdot n_T \cdot < \sigma v > \cdot \epsilon_f \tag{1.10}$$

being ρ_f the fusion power density (W/m^3) and ϵ_f the energy released per fusion reaction (17.6 MeV). Considering a 50% - 50% D-T plasma, it can be deduced that $n_D = n_T = \frac{n}{2}$ which allows developing the previous equation to:

$$\boldsymbol{\rho_f} = n_D \cdot n_T \cdot < \sigma v > \cdot \epsilon_f = \boldsymbol{\frac{n^2}{4} \cdot < \sigma v > \cdot \epsilon_f} \qquad \left[\frac{W}{m^3}\right] \tag{1.11}$$

Only a part of that energy will remain inside the plasma. It is called the alpha fusion power, coming from the alpha particles (He^4). The alpha fusion power can be written as:

$$\rho_{f,\alpha} = \Gamma_{DT} \cdot \epsilon_\alpha \cdot f_\alpha \tag{1.12}$$

where ϵ_α is the fusion reaction energy that goes to the alpha particles (3.5 MeV) and f_α is the fraction of the energy from alpha particles that is transferred to the plasma during its moderation (approximately 1). As these particles remain in the plasma, their energy will contribute to continue its heating.

In order to have fusion, as mentioned previously, it will be necessary that the ions involved retain their energy and stay in a certain region sufficient time to react with another one. This means that the product of this time, also called the confinement time τ_E, and the density of particles must be sufficiently large.

The most promising method of supplying the energy is to heat the D-T fuel to a temperature that makes the velocities of the nuclei high enough to cause the reaction.

This allows deducing that the three most critical parameters to take into account to achieve fusion reaction are:

1. Fuel density
2. Confinement time
3. Temperature of the ions and electrons in the plasma

1.2 Energy balance in a plasma

In order to have a functional reactor that produces energy, it is necessary to have a positive balance of energy. What are the different elements that participate in the plasma energy balance?

1.2.1 Energy losses

There are different kinds of energy losses in a plasma due to different phenomena but the two main ones are:

- Losses by Bremsstrahlung radiation
- Losses by Cyclotron radiation

The **Bremsstrahlung radiation** is produced when a charged particle is deviated or decelerated by another charged particle. This produces the emission of electromagnetic radiation. The power radiated by Bremsstrahlung is calculated as:

$$\boldsymbol{\rho_{br} = 5.35 \cdot 10^{-37} \cdot n_e \cdot T_e^{1/2} \cdot \sum n_i \cdot Z_i^2} \qquad \left[\frac{W}{m^3}\right] \tag{1.13}$$

where the temperature T_e is expressed in keV. n_e is the density of electrons, which is directly related with the density of ions n_i with the formula $n_e = n_i \cdot Z_i$ where Z_i is the atomic number of the ion i (the plasma is globally neutral). This means that in global, the Bremsstrahlung losses are proportional to Z_i^3. In an ideal D-T plasma, $Z_i = 1$ so $Z_i^3 = 1$, which keeps the losses low but, as soon as other elements appear inside the plasma, such as helium (product of the fusion reaction), the global Z_i starts increasing towards $Z_{He} = 2$ (so $Z_i^3 = 8$)).This makes the losses increase at a very fast rate, which will progressively cool the plasma and will end up stopping the fusion reaction. This is why it is very important to have the best possible control on the plasma and the impurities that could fall inside as it could make the whole reaction stop. For this reason, the reactor walls are covered with material with low atomic numbers, in case small fragments could fall inside the plasma. It is also important to keep in mind that the Bremsstrahlung losses depend on the square root of the temperature. The more the temperature increases, the bigger the losses will be. In a perfect D-T plasma, the equation 1.13 can be simplified:

$$\rho_{br} = 5.35 \cdot 10^{-37} \cdot n_e \cdot T_e^{1/2} \cdot (n_D \cdot Z_D^2 + n_T \cdot Z_T^2) \tag{1.14}$$

As for both the deuterium and tritium $Z = 1$ and $n_D = n_T = \frac{n_i}{2}$ this can be developed to obtain:

$$\rho_{br} = 5.35 \cdot 10^{-37} \cdot n_e \cdot T_e^{1/2} \cdot n_i \tag{1.15}$$

and, as in a plasma $n_e = n_i$, the formula is reduced to:

$$\rho_{br} = 5.35 \cdot 10^{-37} \cdot n^2 \cdot T_e^{1/2} \tag{1.16}$$

The **Cyclotron radiation** is due to the energy emitted by charged particles when they are accelerated or deviated by a magnetic field. These losses are smaller than the Bremsstrahlung. As the mass of ions is much bigger than the mass of electrons, the cyclotron losses caused by ions can be omitted as they will be much smaller than the ones caused by electrons, which are much easier to accelerate or deflect. The power radiated by cyclotron is expressed as:

$$\boldsymbol{\rho_c = 5 \cdot 10^{-38} \cdot n_e^2 \cdot T_e^2} \qquad \left[\frac{W}{m^3}\right] \tag{1.17}$$

The cyclotron radiation losses are proportional to the square of the temperature. If it is compared to the Bremsstrahlung losses, it can be observed that:

- At low energy, the losses by cyclotron are much smaller than the losses by Bremsstrahlung.
- It has been seen that $\rho_{br} \propto T_e^{1/2}$ and $\rho_c \propto T_e^2$, which indicates that, at high temperatures, cyclotron radiation losses increase much faster with temperature than Bremsstrahlung radiation.

1.2.2 Plasma energy

The average kinetic energy of a particle in a plasma can be expressed as a function of the temperature of the gas using the Boltzmann constant: $E = \frac{3}{2} \cdot k_B \cdot T$ where k_B is the Boltzmann constant and T is the temperature of the particle. The '3' at the top comes from the number of degrees of freedom of the particle. If this is done for i particles (counting electrons and ions) with densities $n_e = \sum n_i \cdot k_B \cdot T_i$, the total energy that is contained in the plasma per volume unit is:

$$E_{plasma} = \frac{3}{2} \cdot \sum n_i \cdot k_B \cdot T_i \tag{1.18}$$

In the ideal case of D-T reactions where all the elements have $Z = 1$ (meaning that the number of electrons and ions are the same, $n_e = n_i = n$) and are at the same temperature ($T_e = T_i = T$), the equation becomes:

$$\boldsymbol{E_{plasma}} = \frac{3}{2} \cdot n_e \cdot k_B \cdot T_e + \frac{3}{2} \cdot n_i \cdot k_B \cdot T_i = \boldsymbol{3 \cdot n \cdot k_B \cdot T} \tag{1.19}$$

This energy is the one needed to bring the plasma to temperature T. This has to be done using external heating methods.

In 1957, John Lawson defined the minimal conditions that a thermonuclear fusion reactor must have in order to obtain a positive energy balance. The Lawson criterion allows finding the conditions in which the reactor will produce more energy than the one it consumes. The criterion is based on some hypothesis to simplify the problem:

1. The plasma is heated and confined during a certain time τ_E, called the confinement time, during which fusion reactions are produced.
2. The increase of Bremsstrahlung losses due to the appearance of alpha particles in the plasma is not considered.
3. The temperature of electrons and ions in the plasma are equal ($T_e = T_i$).
4. The fuel inside the plasma is a D-T mixture at 50% ($n_D = n_T$).
5. The ions do not disappear by fusion.

The total energy that needs to be inside the reactor to obtain fusion per unit volume is the sum of the energy to bring the plasma to the temperature T plus the energy needed to compensate the losses:

$$E_{in} = 3 \cdot n \cdot k_B \cdot T + \rho_{br} \cdot \tau_E + \rho_c \cdot \tau_E \tag{1.20}$$

The total energy produced by the plasma is exactly the same as te one at the entry plus the energy of fusion.

$$E_{out} = 3 \cdot n \cdot k_B \cdot T + \rho_{br} \cdot \tau_E + \rho_c \cdot \tau_E + \rho_f \cdot \tau_E \tag{1.21}$$

The global efficiency η of the cycle, in case of having a positive balance, is $E_{in} = \eta \cdot E_{out}$. By replacing the terms from the equations 1.20 and 1.21, using the previous equations defined for each kind of power (equations 1.13 for Bremsstrahlung, 1.17 for Cyclotron radiation and 1.19 for plasma energy) and after some manipulations and simplifications, the final expression is:

$$n \cdot \tau_E = \frac{3 \cdot k_B \cdot T}{\frac{1}{4} \cdot < \sigma v > \cdot \epsilon_f \cdot \frac{\eta}{1-\eta} - 5.35 \cdot 10^{-37} \cdot T^{1/2}} \quad \left[\frac{s}{m^3}\right] \tag{1.22}$$

Where $n \cdot \tau_E$ product is defined as the Lawson parameter. However, in many cases, the preferred parameter to represent the evolution of fusion technology and temperature is the so-called triple product of fusion $n \cdot \tau_E \cdot T$. It is know that, in order to reach a self-sustained plasma, the value of the triple product has to be larger or equal to $5 \cdot 10^{21} m^{-3} \cdot s \cdot keV$ The evolution of this triple product has been increasing progressively through the years towards reaching the commercial fusion reactor, as it can be seen in the following figure.

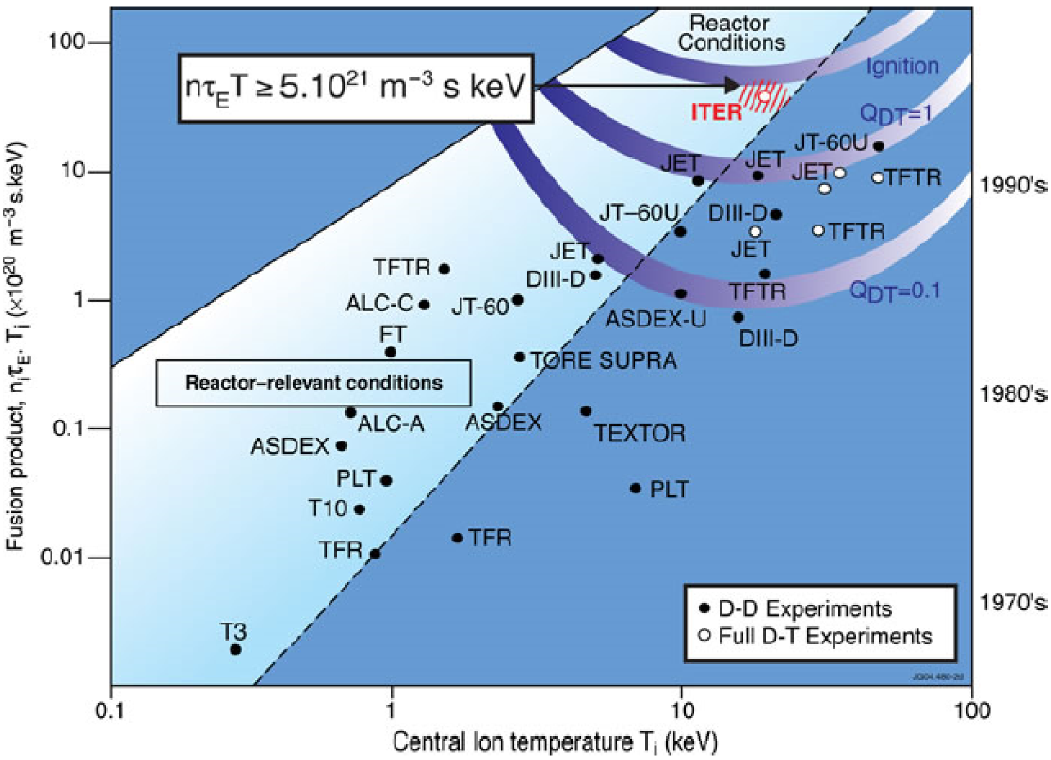

Figure 1.5: Evolution of the triple product of fusion in real reactors.
Source: [4]

The evolution in fusion technology defined two events called *Breakeven* and *Ignition*:

- **Breakeven** is the moment when the reactor produces as much energy (or more) than the one provided externally. From that moment on, the production of energy is possible. However, if at any moment, the external energy supply is stopped, the fusion reactions will stop.

- **Ignition** is the moment from which the fusion reaction can be maintained without the need of having any external energy supply. If the external energy supply is stopped, the fusion reactions will continue. In order to reach this point, the energy provided by the alpha particles generated in the plasma has to be big enough to compensate the losses.

This allows introducing the *Gain Factor* term, which is defined as the ratio between the energy produced by fusion and the external energy supplied to the plasma (E_{ext}). It can be written as:

$$Q = \frac{E_{fusion}}{E_{ext}} = \frac{\rho_f \cdot V \cdot \tau_E}{\rho_{ext} \cdot V \cdot \tau_E} = \frac{\rho_f}{\rho_{ext}} = \frac{\frac{n^2}{4} \cdot < \sigma v > \cdot \epsilon_f}{\rho_{ext}} \tag{1.23}$$

As the energy ϵ_f released in each fusion (17.6 MeV) is more or less five times the energy of the alpha particles (3.5 MeV), Q can also be written as:

$$Q = \frac{5 \cdot \rho_\alpha}{\rho_{ext}} \tag{1.24}$$

Taking into account the definition of the two events presented, the gain factor corresponding to reaching the Breakeven event is $Q = 1$. This corresponds to an alpha particle power of 20% of the applied external power. At ignition, the gain factor would be $Q = \infty$ (as ρ_{ext} is zero when ignition is accomplished). It is considered that, in order to have a commercial fusion reactor, the amplification factor should be at least 20.

Combining this with the energy balance done previously, both events can be expressed as energy balances:

- At Breakeven, the external energy supply plus the heating from the alpha particles have to maintain the plasma hot enough to have fusion energy and compensate the losses by radiation (Bremsstrahlung and cyclotron).

$$\rho_{ext} + \rho_\alpha = \frac{3 \cdot n \cdot k_B \cdot T}{\tau_E} + \rho_{rad} \qquad (\rho_{rad} = \rho_{br} + \rho_c) \tag{1.25}$$

- At Ignition, the heating from the alpha particles is enough to keep the plasma hot and to compensate all the losses.

$$\rho_\alpha \geq \frac{3 \cdot n \cdot k_B \cdot T}{\tau_E} + \rho_{rad} \tag{1.26}$$

The following figure represents the profile of each type of power to keep the plasma in equilibrium for a constant confinement time and reaching ignition at 10 keV.

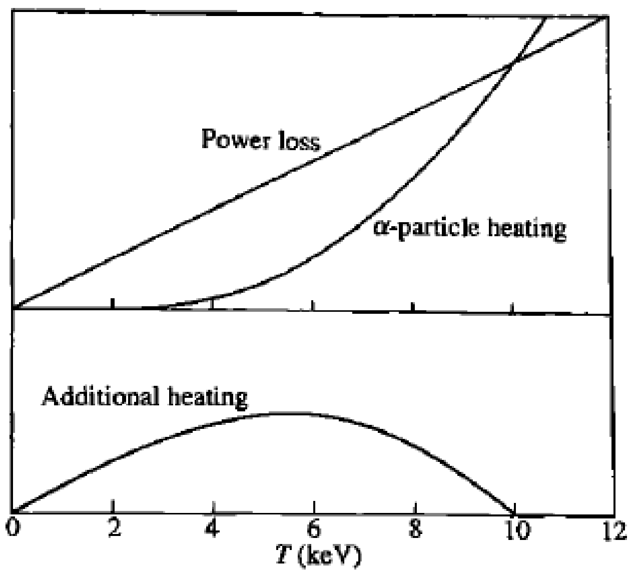

Figure 1.6: Power balance as a function of temperature.
Source: [3]

The previous plot shows that, in order to reach ignition, the availability of external additional heating is mandatory to bring the plasma up to the temperature where this event starts.

1.3 Types of confinement

In order to obtain the required conditions to get fusion power, there are different existing technologies to obtain fusion energy nowadays. The first classification depends on the type of confinement of the plasma. The main goal at the end is to achieve a triple fusion product big enough to reach a state in which fusion becomes commercially sustainable, getting a major energy output than the energy input ($Q > 1$).

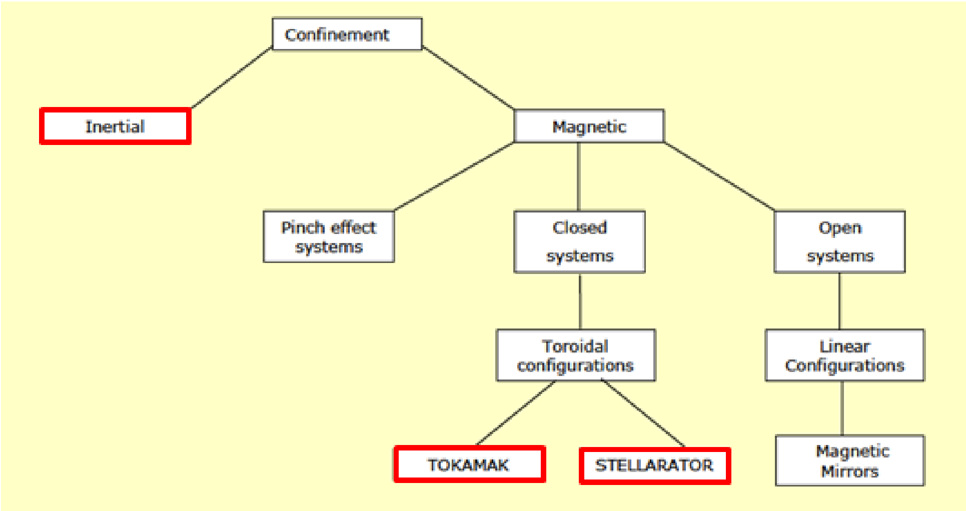

Figure 1.7: Different technologies to obtain fusion energy.
Source: [2]

The two main families of fusion technologies are the ones based on inertial confinement and the ones with magnetic confinement. There are many experimental reactors all over the world for both types of confinement, each one of them trying to reach the goal of creating a sustainable and economically viable commercial reactor for the future. Both systems are in permanent competition to see which one gets the best results in terms of generated fusion power, triple product, performance, ... to prove which is the best technology.

- Inertial Confinement Fusion (or ICF) attempts to initiate fusion power by heating and compressing the fuel, which is typically stored in a very small pellet that contains a mixture a deuterium and tritium (seeutur Figure 1.8). The way of getting fusion is by heating this very small pellet with powerful energy beams of electrons, ions or lasers in order to heat the outer layer (picture 1 in Figure 1.9). This heating would make the outer layer explode, generating shock waves towards the centre that would compress and heat the fuel (picture 2).This implosion or compression allows obtaining very high temperatures (around $100 \cdot 10^6$ K) and densities in the fuel (the plasma reaches an ion density of around $10^{29} ions/m^3$), enough to create a plasma and generate fusion (picture 3).The energy released in the fusion reaction plus the heating of the alpha particles will contribute heating the rest of the fuel, generating new fusion reactions (picture 4).

Figure 1.8: Picture of a pellet.
Source: Web picture

  This process is very fast (of the order of milliseconds), making the confinement time very short. The released energy will heat a cooling system that will then undergo a typical Rankine thermal cycle to produce electricity.

The drawback of this system is that this process has to be done for each pellet one after another: after one pellet is burned, a new one replaces it and the process starts again. The energy beams that heat up the pellet use a huge amount of energy each time and have a very low efficiency. This, combined with the low efficiency of the Rankine cycle, make this kind of system still far away from the $Q = 1$ objective.

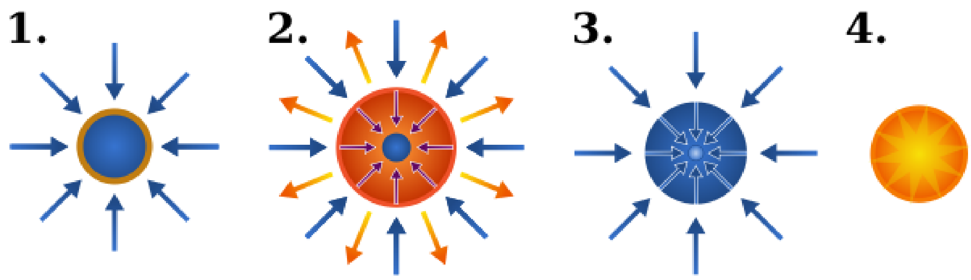

Figure 1.9: Inertial confinement fusion mechanism.
Source: Web picture

- Magnetic Confinement Fusion (or MCF) is the most popular approach nowadays, where the technology goes towards high temperatures, higher confinement times (of the order of seconds or even minutes so far) but much lower ion density in the plasma (around $10^{20} ions/m^3$).

  This system is based on the idea of having the plasma 'floating' inside a strong magnetic field. This magnetic field would keep the particles at high temperature far from the walls of the reactor in order to protect both the plasma (from possible impurities from the wall falling inside the plasma and increasing the losses) and the walls (dangerous for materials when working with such high power with longer confinement times from the point of view of heat load). This can be done thanks to the fact that the plasma is a mixture of ions and electrons, both being electrically charged particles that can be confined within a magnetic field.

  Magnetic confinement reactors are closed systems that make the plasma rotate inside a reactor that has a toroidal configuration. The problem of toroidal geometry is that having closed magnetic lines make instabilities appear. One of the reasons is that the magnetic field is not constant everywhere around the torus: it is stronger in the region of the inner radius and lower at the external radius. This provokes a vertical electrostatic field that separates ions and electrons between top (ions) and bottom (electrons).

  The way of solving this problem is by having magnetic lines that do not close on themselves. This means that a rotation or torsion has to be applied to the magnetic field to change the shape of the magnetic lines, which can be done in two ways:

  - External helical conductors: *Stellerator*
  - Inducing an internal current in the plasma: *Tokamak* (which comes from the Russian: TOroidal CHAmber with MAgnetic Coils)

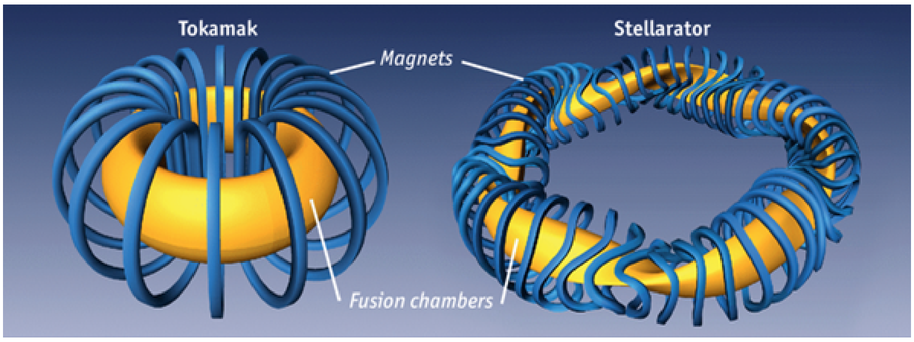

Figure 1.10: *Tokamak* and *Stellerator* reactors.
Source: Article in 'The Economist' journal

Both the inertial confinement and the magnetic confinement fusion have to deal with the consequences of the Lawson criterion and the triple fusion product: In ICF, the density of the particles is very high (about 9 orders of magnitude higher than in MCF) but the confinement time is much smaller than in MCF.

Each one of this confinement systems has its own way of dealing with the triple fusion product: one through high densities and the other one by trying to get long confinement times. In both cases, the order of magnitude of temperatures reached by the plasma is similar.

Both approaches have given good results over the years but are still far from reaching the needed triple fusion product to have a sustainable and viable reactor that could be use at the commercial level. The ITER project, a magnetic confinement fusion tokamak reactor, is aiming to reduce this difference.

Chapter 2

ITER and the role of Fusion For Energy (F4E)

2.1 ITER

The International Thermonuclear Experimental Reactor (or ITER, meaning 'the way' in Latin) is a major international experiment aiming to demonstrate the scientific and technical feasibility of fusion as an energy source.

It should generate some 500 MW of fusion power over periods of around seven minutes under conditions similar to those expected in an electricity-generating fusion power plant. ITER will allow scientists and engineers to develop, in the future, demonstration fusion power stations that will produce electricity.

The ITER *Tokamak* machine is being constructed in Cadarache in the South of France with components that are provided by the members. Seven international parties participate in the ITER project:

- China
- European Union
- India
- Japan
- Russia
- South Korea
- United States

Collectively the parties taking part in ITER project represent over one half of the world's population and 80% of the global GDP (Gross Domestic Product). The ITER agreement is open for accession or cooperation with other countries that have demonstrated a capacity for specific technologies and knowledge and are ready to contribute to the project. The European Union, as host party, will contribute up to about 50% of the costs and the other parties approximately 10% each.

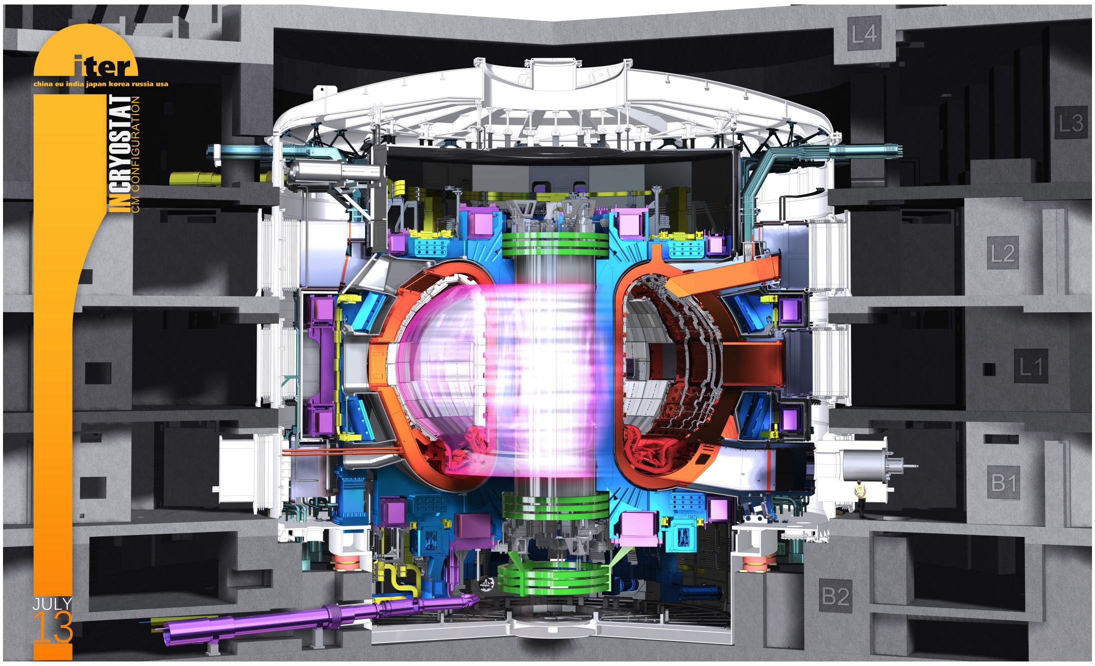

Figure 2.1: Representation of the ITER reactor.
Source: ITER Organization official website

2.2 Fusion for Energy (F4E)

Fusion for Energy (F4E) is the European Union's organization responsible for Europe's contribution to ITER. The organization was created by a decision of the Council of the European Union in order to meet three objectives:

1. Provide Europe's contribution to ITER: ITER is the world's largest partnership aiming to demonstrate fusion as a viable and sustainable source of energy. F4E works together with European industry and research organisations to develop and manufacture the components that Europe will provide to ITER with around 220 contracts. It also provides the EU's financial contribution to the project, which mostly comes from the European Community budget. Among its other tasks, F4E supervises the preparation of the site where ITER is being constructed and arranges for European staff to be available to the ITER International Organization. It also supports research and development for ITER. F4E plays an important role in preparing Europe's participation in the operation of the reactor.

2. Support fusion research and development initiatives through the *Broader Approach Agreement*: F4E participates in the Broader Approach, an international agreement with Japan designed to accelerate the development of fusion energy by cooperating on a certain number of projects of mutual interest. These projects, including preparations for a new materials testing facility, are designed to help and complement ITER by filling possible knowledge gaps. Through F4E, the European Union has agreed to provide components, equipment, materials and other resources for the Broader Approach, prepare and coordinate the European participation in the initiative and make European staff and funding available. One of the big milestones of this agreement has been the recent completion of the disassembly and upgrade of the JT-60 fusion reactor to get the fully superconducting JT-60 SA reactor in Naka (Japan). This new modern reactor will be a platform to perform tests and experiments that will help gaining knowledge and experience for the ITER reactor.

3. Contribute towards the construction of demonstration fusion reactors (DEMO): F4E has progressively started to implement a programme of activities to prepare for the first demonstration fusion reactors (DEMO) beyond ITER which could generate significant amounts of electricity. Other related projects include the International Fusion Materials Irradiation Facility (IFMIF) designed to develop materials that can withstand the conditions expected in a fusion reactor. By capitalising on the activities carried out for ITER and the Broader Approach, Europe is an excellent position to carry fusion forward as a clean and sustainable energy source for the future.

The amount of fusion energy a tokamak is capable to produce depends on the number of fusion reactions that are produced in its core. It has been proved that the bigger the vessel (reactor), the bigger the volume of the plasma and then the higher the potential number of fusion reactions, which is why ITER will be bigger than any other fusion reactor created so far.

The volume of the plasma in ITER will be ten times bigger than in the biggest tokamak reactor existing nowadays. This will allow the reactor having bigger plasmas and better confinement (which leads to a higher confinement time). The machine should accomplish the following objectives:

- Produce 500 MW of fusion power: the world record of fusion gain factor has been obtained by JET (Joint European Torus), the European tokamak located in the U.K., after getting 16 MW of fusion power from a total input power of 24 MW ($Q = 0.67$). ITER aims to obtain a gain factor of ten ($Q = 10$), obtaining 500 MW of fusion power from 50 MW input power. This will prove that tokamak fusion reactors are a suitable energy source for the future.

- Demonstrate the integrated operation of technologies for a fusion power plant: the ITER reactor is a huge challenge that bring all kind of different technologies beyond their limits, generating the need of inventing, creating and manufacturing technology, components and systems that did not exist before. The problem becomes even more complex when all this cutting-edge technologies have to co-exist and work in harmony in the same machine. The ITER project is pushing the edges of technology and represents a huge revolution in many different fields.

- Achieve a deuterium-tritium plasma sustained only with internal heating (from alpha particles). This will prove that the plasma can be self-sustained in long pulses without the contribution of external energy sources. So far, the plasma confinement time record is held by the French *Tore Supra* reactor, which was able to maintain a plasma pulse for approximately 6 minutes and 30 seconds. ITER wants to achieve much longer plasma pulses that would ensure the energy supply of future fusion reactors to the grid.

- Test the tritium breeding blankets: the difficult management of tritium makes these breeding blankets the best way of getting the necessary available tritium to have a continuous fuel supply for fusion reactions to continue in the reactor. The ITER reactor will be the first real reactor that will allow testing these blankets inside the vessel.

- Demonstrate the safety of a fusion reactor: in front of the public opinion and the world, ITER has the crucial role of proving that fusion is a sustainable and safe energy source that has no consequences to the environment. This is a key point in order to start building commercial reactors in the future.

As it has been said, it is essential to first bring the plasma to the operating range conditions in order to make the fusion reactions occur and meet the objectives mentioned. To do so, the ITER reactor has several different heating systems that will allow reaching the 150 million °C.

2.3 Tokamak heating systems

As it has been explained previously, in every kind of fusion reactor it is necessary to have an external source of energy in order to heat the plasma and bring it to its operational point and, unless this point is ignition, keep it at the right temperature to generate fusion reactions. In Tokamak fusion reactors there are different kinds of heating systems.

The first system is the *Ohmic heating*. There is an internal current induced inside the plasma. The plasma acts as a resistor, which generate heat losses due to the Joule effect. These current losses will contribute heating the plasma. The problem of plasma is that, the more it is heated, the less resistant it becomes: when the temperature reaches 1 keV [12], the plasma resistivity is very small, which means that the heat losses due to Joule effect will progressively decrease until being negligible. However, in order to have a good plasma the system has to be heated up to more than 10 keV, which makes clear that Ohmic heating is far from being enough. In the case of the ITER reactor aims to achieve a gain factor of 10 with a 500 MW fusion power reactor, which means 50 MW of external heating are needed. In this case the contribution of ohmic heating would only cover approximately 0.5 MW of heating power, approximately 1% of the total required.

The second one is the *Neutral Beam Injection*, which consists in injecting highly energetic beams of neutral atoms with the goal of making them collide with the ions of the plasma and transfer part of their energy to them, increasing the temperature. This system can send neutral particles at up to 1 MeV, which means it can be used during the whole operation of the plasma.

The third system is the *Radio Frequency (RF) heating*, which consists in sending electromagnetic radiation that will directly heat:

- The electrons, for the *Electron Cyclotron Resonance Heating* (ECRH) system, working at 170 GHz.
- The ions, for the *Ion Cyclotron Resonance Heating* (ICRH) heating, working between 40 and 56 MHz.

The RF waves transfer their energy to the particles, increasing their temperature (in a similar way a microwave does). The Electron Cyclotron heating system is also used to deposit heat in very specific places in the plasma (thanks to a steerable launcher), as a mechanism to minimize the progress of instabilities that could lead to the cooling of the plasma. In comparison to the ICRH system, the ECRH has the advantage that the beam is very easy to couple with the plasma and allows the source to be far from the plasma, simplifying the design and the maintenance tasks. This power will be provided by high-frequency *Gyrotrons*.

In ITER, a total of 73 MW of external heating power will be available (from which 50 MW will be used) combining:

- 33 MW of Neutron Beam Injection power (two devices injecting 16.5 MW each).
- 20 MW of Ion Cyclotron RF heating injected (two ion cyclotron resonant heating antennas injecting 10 MW each).
- 20 MW of Electron Cyclotron RF heating injected (24 MW coming from 24 gyrotrons delivering 1 MW each. The difference of 4 MW is due to the losses in the transmission lines from the gyrotrons to the launchers).

This project will be focused on the operation and control of the *Gyrotrons* in order to be able to deliver the 1 MW of power to the plasma each.

Chapter 3

The Gyrotron

The Gyrotron (from 'gyrating electron') is a 'vacuum electron tube in a strong magnetic field'[6] which can deliver up to 1 MW of continuous wave in a frequency range from 70 to 200 GHz. The gyrotron has a 2 MW power and efficiency around 50% (1 MW output power).

3.1 Description of the gyrotron

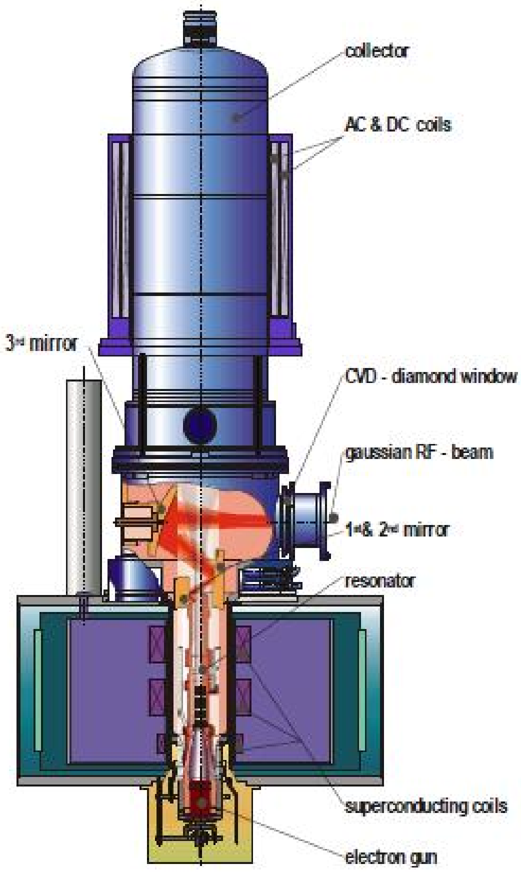

Figure 3.1: Representation of the gyrotron. *Source: [5]*

The first gyrotrons were built in 1964 by the USSR as a high power source for low level flight radar but after that, their main application has been heating fusion plasmas.

The electron-cyclotron interaction takes place between an RF field and electrons rotating under the influence of a magnetic field. When the RF field is the field of a waveguide mode close to cut-off and the RF frequency is close to the cyclotron frequency or harmonics of it, it is called *Gyrotron Interaction.*

The principle of operation of a gyrotron is to accelerate electrons using a magnetic field, generating an RF at the right frequency that can then be extracted through the output window of the device.

These electrons are extracted from an emitter called the *Cathode Filament* applying a high differential of voltage, which will create an electric field. This system is called the *Electron Gun* (EG). The electrons are then directed towards the gyrotron tube first with the electron gun, using the *Gun Coils* and then with the *Superconducting Magnets Coils*, which will accelerate the electron beam.

The electrons oscillate in presence of an external magnetic field, rotating around the field lines, which generates electromagnetic waves.

Both coils systems and the trajectory of an electron can be seen in Figure 3.2.

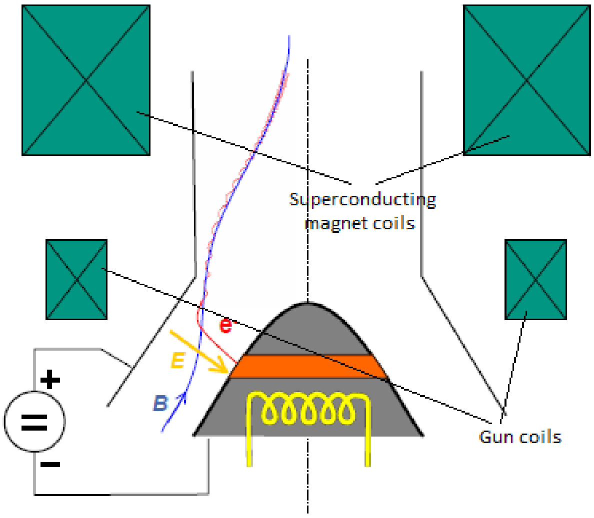

Figure 3.2: Extractions and deflection of the electrons.
Source: [6]

As the electrons move upwards, the magnetic field becomes higher, which makes the parallel component of the electrons velocity decrease as the perpendicular component increases, making the electrons rotate faster and faster around the field lines. This introduces the *Pitch Factor* α, defined as the ratio between the perpendicular and the parallel component of velocity with respect to the field lines $\left(\alpha = v_{\perp}/v_{\parallel}\right)$. The electron beam progressively becomes an annular beam.

After the area of extraction, the electron beam arrives in a compression zone called the beam tunnel. In this zone, absorbing material is located on the walls in order to suppress and absorb unwanted parasitic oscillations. The area of the compression zone is progressively reduced until arriving to the *gyrotron cavity* (also called resonator).

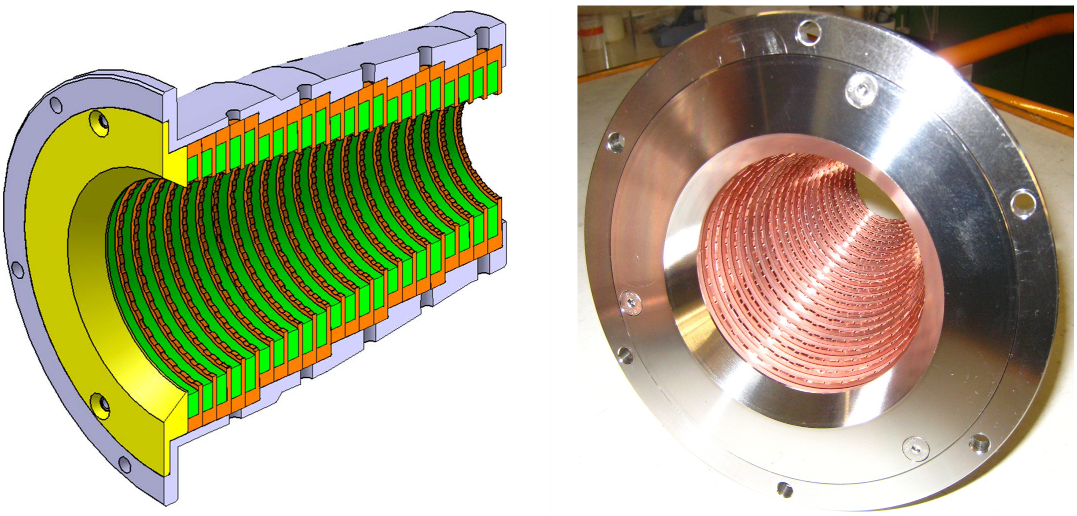

Figure 3.3: **a)** Representation of the compression zone with the absorbing material.
b) Picture of the compression zone of a real gyrotron.
Source: [6]

The resonator is the area where the frequency and mode of the RF will be determined. The mode is the state of excitation of an electromagnetic wave in which all the components of the system will be affected by a sinusoidal shape under a specified frequency. Each mode is characterized by one or several frequencies. Each mode stores a specific amount of energy due to the sinusoidal excitation.

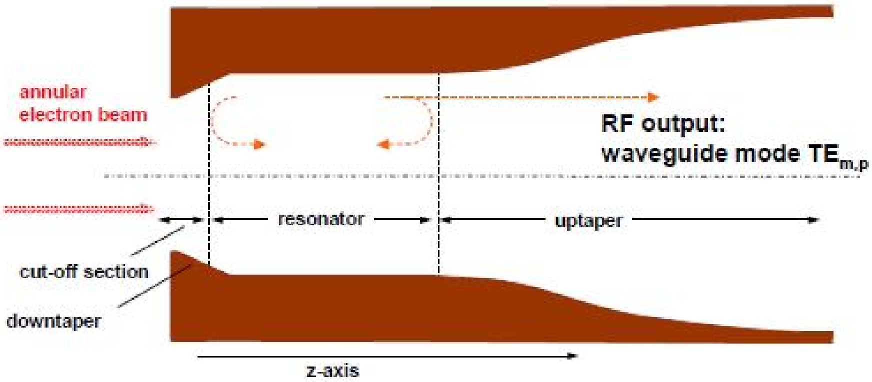

Figure 3.4: Scheme of the geometry of the resonator.
Source: [6]

The resonator or cavity is a zone with a very specific geometry (see Figure 3.4).

- On the left side, the downtaper at the electron entrance is used to minimize the RF power travelling backwards towards the electron gun (RF reflections can appear).
- The central part is where the mode and the frequency are defined.
- On the right side, the uptaper to increase progressively the diameter without affecting the frequency and mode of the RF.

The value of α in the cavity should be as high as possible in order to increase the efficiency. The quality of a resonator depends on its losses.

- Unloaded quality factor Q_0, related to wall losses (skin effect), defined as:

$$Q_0 = \omega \cdot \frac{stored\ energy}{cavity\ power\ losses} \tag{3.1}$$

- External quality factor Q_{ext}, related to coupling losses, defined as:

$$Q_{ext} = \omega \cdot \frac{stored\ energy}{coupling\ losses} \tag{3.2}$$

- Total losses Q_L, taking into account all losses:

$$Q_L = \omega \cdot \frac{stored\ energy}{total\ losses} \tag{3.3}$$

which, combining equations 3.1, 3.2 and 3.3 can also be written as:

$$\frac{1}{Q_L} = \frac{1}{Q_0} + \frac{1}{Q_{ext}} \tag{3.4}$$

For gyrotrons operated in such high order modes, it is necessary to adapt a quasi-optical mode converter to transform the cavity mode into a fundamental Gaussian wave beam, which is the desired shape of the beam that will be sent out of the gyrotron.

This is done by means of a device called the *launcher*, which is a helical-shaped tube that changes the mode distribution of the beam. In order to do that, the RF wave is focused inside the waveguide by very small deformation on the inner wall to make the beam follow this shape.

At the exit of the launcher, the RF wave is sent against three different mirrors that will allow sending the beam through the output RF window of the gyrotron.

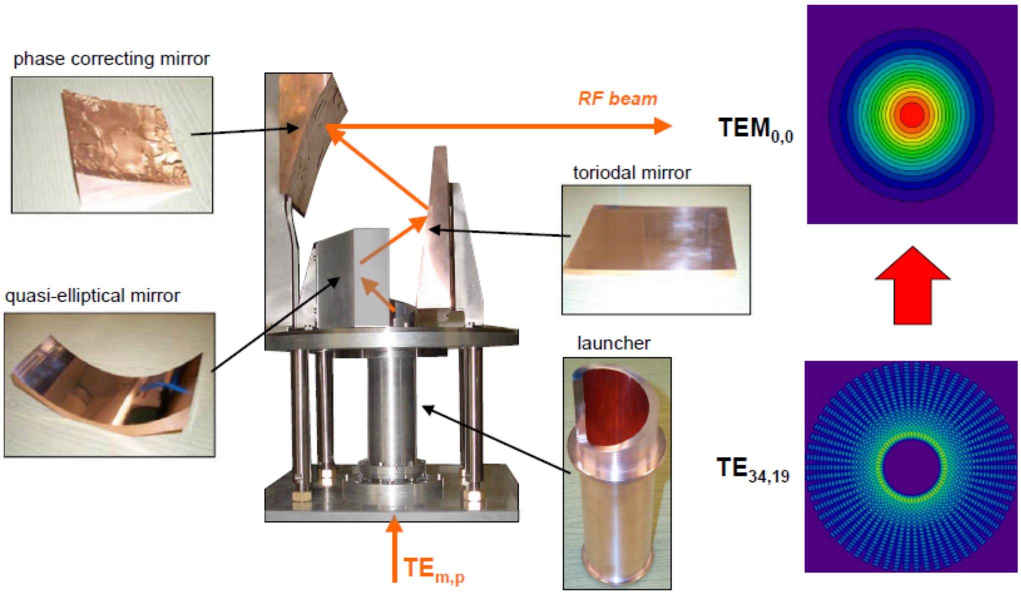

Figure 3.5: Mode conversion using the launcher and the optical mirrors.
Source: [7]

The whole path of the electron beam from the cathode to the RF window and the power density of the beam from the launcher to the RF window can be seen in the following figure.

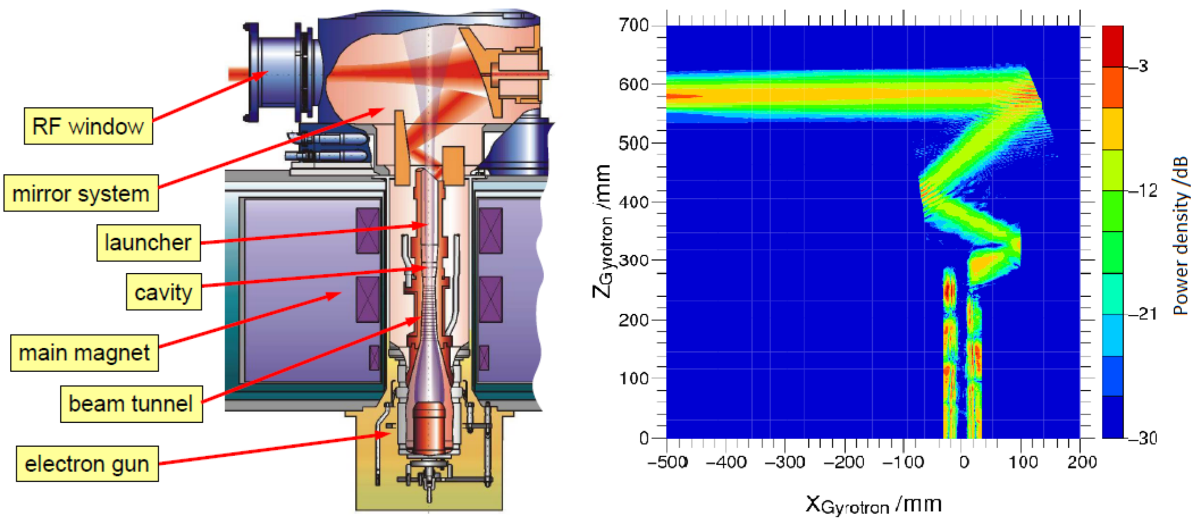

Figure 3.6: **a)** Path of the electron beam from the Cathode Filament to the RF window.
b) Power density of the RF beam from the launcher to the RF window.
Source: [6]

As it is essential that the gyrotron works under perfect vacuum, it has to be sealed everywhere, including the RF output window. In modern gyrotrons, this is achieved using chemical vapor deposition (CVD) diamond disks, which are almost transparent to the RF waves and at the same time allow the sealing of the device. By being made of diamond it does not melt due to the heat load that is partially deposited on it when the RF beam crosses and at the same time it does not change the mode or shape of the beam.

Right after going through the RF window, the wave would enter inside the *Matching Optical Unit* (or MOU), a system that couples the RF power from the RF output window of the gyrotron to the *Transmission Line* (TL) waveguide (which are the ones that will drive the signal up to the launchers that will send it inside the reactor core). The MOU has some mirrors inside that will modify the mode of the RF wave to the one needed inside the reactor.

At the same height as the RF output window, there is another exit connected to a *Relief Load*. In for any reason the mode of the RF wave or its rotation are wrong, the beam would not leave through the diamond window as it would not be oriented in the right way by the launcher and the mirrors. This 'bad' RF wave would then be sent out of the gyrotron to this relief load. If this load was not there, the wave would create a local hot spot on the wall of the gyrotron that could destroy it.

However, as it has been said before, the gyrotron has an efficiency of 50%, which means that from the 2 MW of power, only 1 MW goes through the RF window. The other 1 MW of power stays inside the gyrotron in the form of electron beam. This energy has to be dissipated somehow to ensure the integrity of the components and allow the continuous operation of the gyrotron.

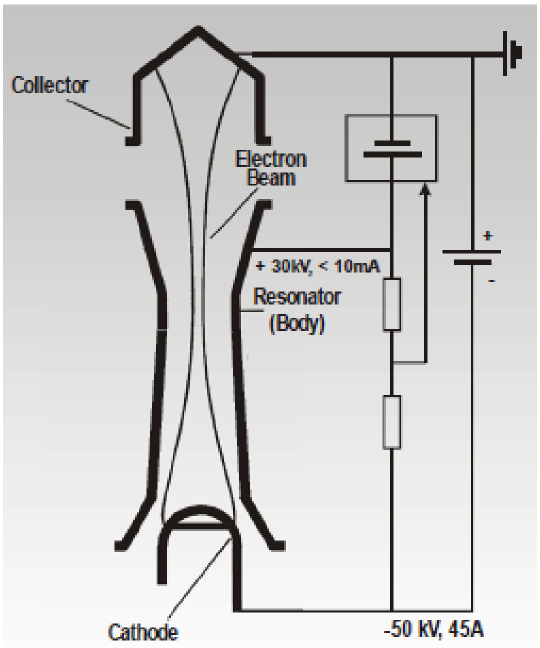

Figure 3.7: Voltage differences in the gyrotron.
Source: [6]

The *Collector* is the element in charge of absorbing the remaining energy of the electron beam. It consists in a long copper cylinder located on top of the gyrotron where the electrons will impact, depositing their remaining energy in the form of heat.

Right before the RF window, there is an element called the *DC break* in which the voltage is highly increased: In the cathode, the voltage is -50 kV whereas in the DC break it is at 30 kV, which makes a -80 kV voltage differential that is responsible of accelerating the extracted electrons upwards. However, the collector is connected to ground, which means that the voltage difference between the DC break and the collector is 30 kV. This huge change in the voltage differential will decelerate the high-energy electrons in the electron beam, progressively reducing their energy (see Figure 3.7). This energy reduction will also significantly reduce the heat load on the collector surface.

In order to have a uniform distribution of the heat load all around the collector's surface, additional coils are used to sweep the electron beam over the whole surface. This sweeping signal consists in a periodic triangular wave that changes the Z position where the electrons will impact the walls of the collector. These sweeping coils will avoid the creation of local heat points that could compromise the integrity of the whole gyrotron.

All the power losses that occur during the whole process from the extraction of the electrons to the exit of the RF wave and the impact of the electrons on the collector walls require a good, safe and global cooling system that has to make sure that none of temperatures of the components of the gyrotron rises too much. For obvious reasons, the most critical part is the collector as it is the one where the biggest amount of heat is deposited. This is why its whole surface is full of cooling pipes that will keep it at the right temperature.

3.2 Gyrotron Auxiliary systems

The RF power source is composed of the gyrotron tube and the gyrotron operation system with various auxiliary components. The gyrotron operation system consists of multi-systems and each subsystem provides a necessary functionality to operate the gyrotron tube. The components will be described one by one in the following subsections.

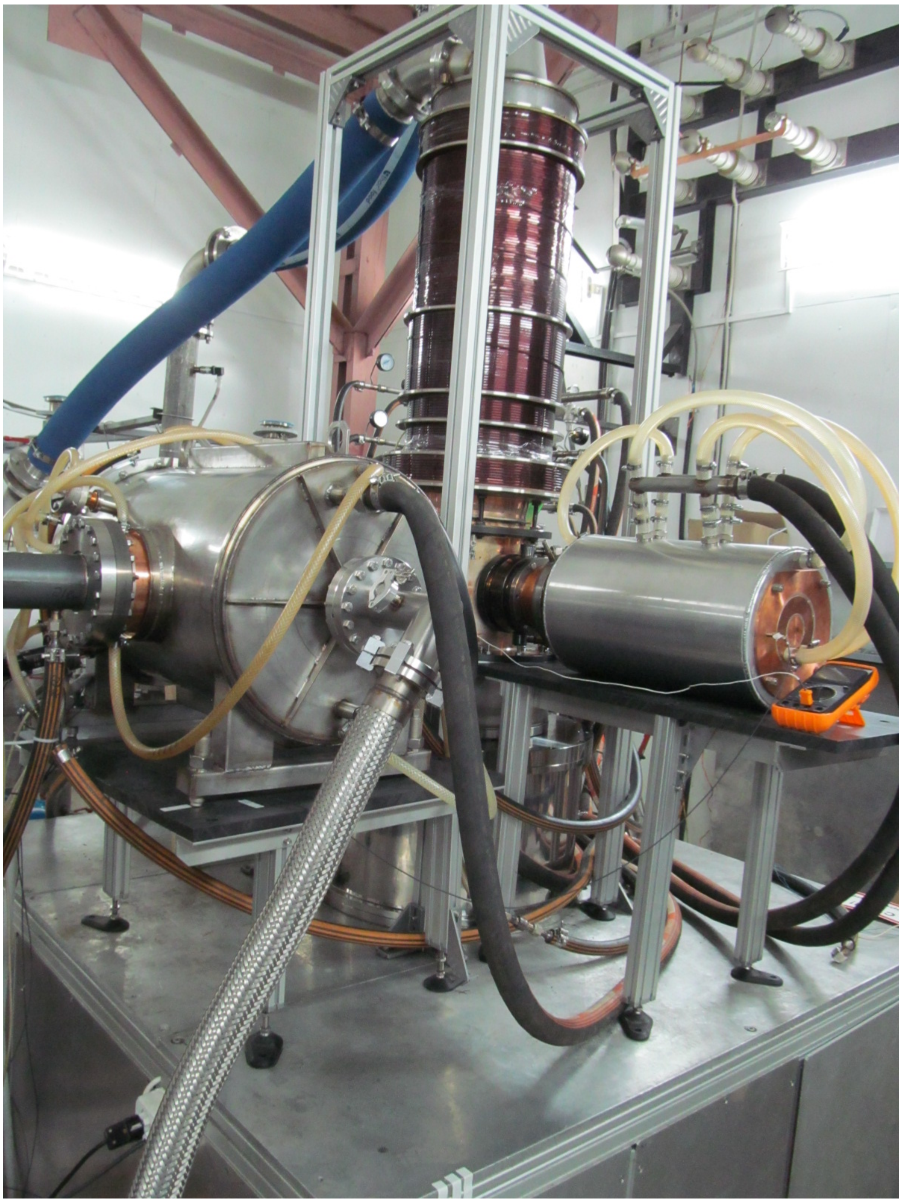

Figure 3.8: The gyrotron and its components.
Source: [8]

3.2.1 Gyrotron tube

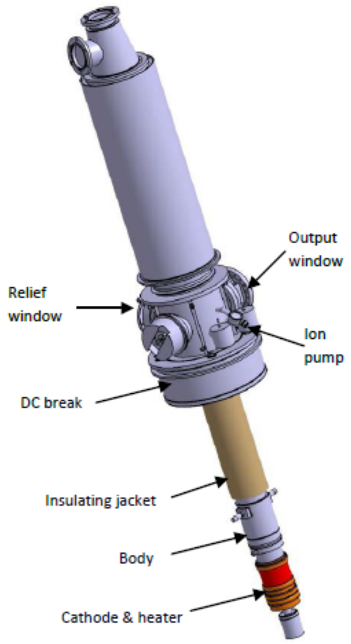

Figure 3.9: Model of the gyrotron tube.
Source: [9]

The gyrotron tube is the main element of the heating power source system. It includes all the different sections described in the previous part (CVD diamond disc window, cavity, collector, relief window, DC break, mirrors, etc.).

Another system that is integrated in the gyrotron tube is the ion pump. The gyrotron has from two to four ion pumps connected at the height of the output window in charge of guaranteeing the vacuum inside the gyrotron tube. When the gyrotron tube is manufactured, it is done with vacuum inside in order to avoid the appearance of electric arcs inside the tube due to the high voltage differences applied. These arcs would completely destroy the component.

The ion pumps are there to make sure that this vacuum is kept. They work ionizing the gas inside the tube and employ a strong electrical potential that attract and capture the ions and send them out of the component. They are working continuously, even if the gyrotron is no being operated.

3.2.2 Matching Optical Unit (MOU)

The MOU is a device in charge of coupling the RF power coming from the RF window to the Transmission Line (TL) wave-guide. This is done using quasi-optical mirrors that convert the beam from the gyrotron to the proper profile beam needed to be injected inside the reactor core.

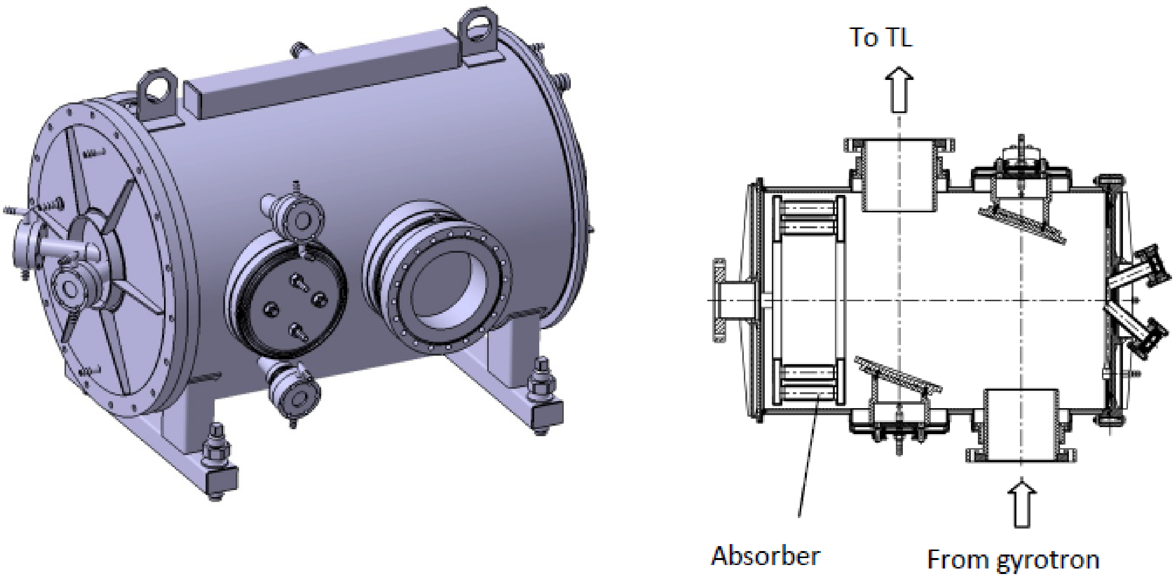

Figure 3.10: Model and schematics of the MOU.
Source: [9]

3.2.3 Super conductive magnet (SCM) system

Figure 3.11: SCM magnet picture.
Source: [10]

The superconductive magnet is the system in charge of driving the electrons inside the compression zone and along the cavity. This magnetic field is very important for the gyrotron operation as it determines the RF frequency.

These coils are cooled by a cryogenic system that has to make sure that the coils are kept under superconducting conditions. This cryogenic system is operated under a liquid He free system works with a compressor. As this system is so important for the operation of the gyrotron, it includes a temperature monitor and sensor to have a constant control on the temperature of the coils.

3.2.4 Oil Tank

The Oil Tank is a tank full of insulating oil located right under the gyrotron tube. It insulates the electrodes of the gyrotron electron gun (HVPSs) and the cables that are connected to the Cathode Filament.

The oil is in permanent movement in order to extract the heat produced by the electron gun, which is why the way of controlling the right operation of the Oil Tank is through a flow sensor.

3.2.5 Cathode Filament

The cathode of the gyrotron electron gun has a filament (or heater) that produce the electrons that will be then be extracted to create the electron beam. It produces a high current on the filament that can be adapted to the needs of the gyrotron pulse thanks to a feedback loop in its control system. The reference current is gradually modified until reaching the right electron beam current inside the gyrotron.

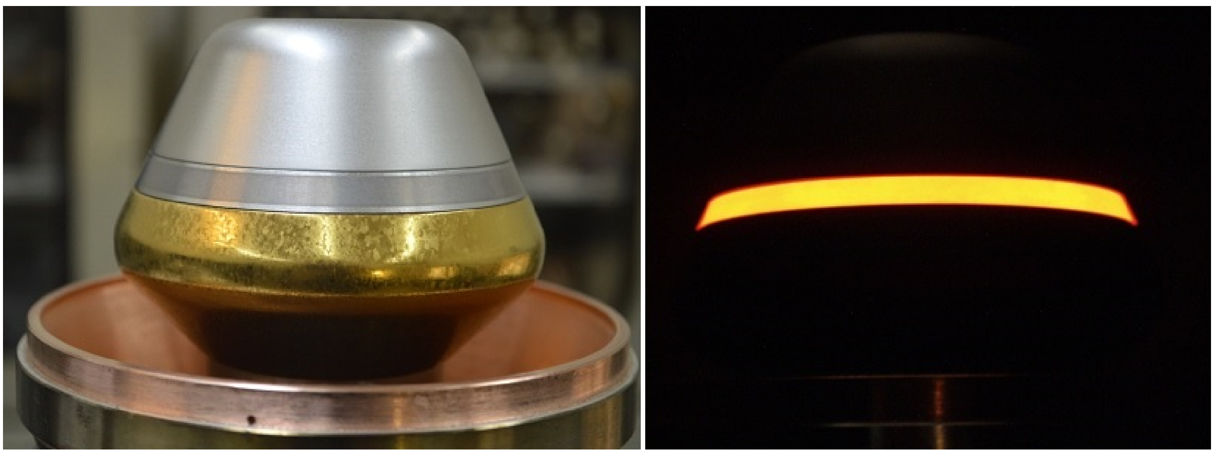

Figure 3.12: a) Cathode Filament geometry and structure.
b) Cathode filament at operating temperature under vacuum.
Source: [8]

3.2.6 Gyrotron Cooling System

The gyrotron and auxiliary devices, such as the MOU, the Relief Load or any of the other subsystems have various water channels to make sure they stay in the right operating range of temperature during their operation. The flow rate and temperature of each cooling subsystem is measured in order to make sure that everything is working correctly.

3.2.7 Vacuum system

After exiting the gyrotron tube through the RF window, the RF wave has to travel inside the MOU and the Transmission Line under vacuum. There are two pumps that make sure that this vacuum is maintained when the gyrotron has to be operated (in this case, if the gyrotron is not in operation or about to start operating, it is not necessary to use these pumps as they do not have any effect of what happens inside the gyrotron tube).

The system consists in one main vacuum pump, which allows reaching a first level of vacuum, and a turbo pump, which allows achieving a better vacuum. The turbo pump cannot be turned on from the beginning as it required a minimum level of vacuum to work. This is why the main vacuum pump is turned on first and, when a certain vacuum threshold is reached, the turbo pump is started.

3.2.8 Collector coil system

The collector coil system is divided in two elements: the *Collector DC* and the *Collector Sweeping coils*.

The combination of both is used to generate a periodic triangular signal that diverts the electrons entering inside the collector in order to make them impact in different places of the collector walls. This uniform distribution reduces the heat load on the walls of the collector.

3.2.9 Gun Coil System

The Gun Coil system is in charge of helping in the extraction of the electrons from the Cathode Filament by means of an electric field. It is where the electron beam is created. These coils are also responsible of driving the electrons upwards inside the tube (before reaching the SCM coils). The electric field generated by these coils can be modified in order to extract more or less electrons and adapt the pulse to the needs of the reactor core.

3.2.10 Arc detector system

The high voltage differences applied inside the gyrotron are big enough to ionize a gas and generate electric arcs inside the device. This should not happen as the gyrotron tube should operate under perfect vacuum but if, for example, a particle from the tube detaches and falls inside the tube, this kind of phenomena could appear.

An electric arc carries big amounts of energy and if any appeared inside the gyrotron it could destroy the whole component in the range of few microseconds. This is why it is essential to have an arc detector system with a very fast control system that can turn off the gyrotron before it happens. This detector works as a light sensor, that is calibrated to the gyrotron conditions so that it is triggered if there is a light emission higher than the normal one.

3.2.11 High Voltage Power Supplies (HVPSs)

In order to make the gyrotron work and produce RF waves it is necessary to extract electrons from the filament and create an electron beam. This is only possible thanks to two high voltage power supplies that, when turned on, create a voltage difference that is high enough to extract the electrons from the filament and make them travel all along the gyrotron tube.

Two power supplies are necessary because there are two main regions inside the gyrotron tube: a first part where the electrons are accelerated (from the Cathode Filament to the DC break) and the other one where the electrons with the remaining energy are decelerated before impacting against the collector walls.

The first power supply is called the *Main Power Supply* (or MPS). It is connected to the ground and to the cathode, applying a potential of -50 kV. The second power supply is called the *Body Power Supply* (or BPS) and it is connected to the ground and the DC break point (also called the body), applying a potential of 30 kV. The MPS, the BPS and the collector are all connected to the same ground. These connections where already shown in Figure 3.7.

With this configuration, the differential voltage applied in the acceleration zone is

$$U_{acc} = U_{cathode} - U_{body} = -50 - 30 = -80\,kV \tag{3.5}$$

whereas in the deceleration zone it becomes

$$U_{decel} = U_{body} - U_{collector} = 30 - 0 = 30\,kV \tag{3.6}$$

The MPS consists in a set of modules connected all together to provide the necessary voltage. Each MPS provides voltage to two gyrotrons (also called a gyrotron pair), whereas there is one BPS for each gyrotron.

The operation of the two HVPSs has to be synchronised in order to guarantee the safety of the gyrotron:

- For the turning on sequence,the trigger signal to turn on is sent to the MPS. The output voltage of the MPS will then start ramping quickly and, when it reaches a certain threshold and after a delay time T_1, the trigger signal to turn on is sent to the BPS.
- For the turning off sequence it works the opposite way, first the trigger signal to turn off is sent to the BPS. The output voltage of the BPS will then start decreasing fast and, when it reaches a given threshold (different from the previous one) and after a delay time T_3, the trigger signal to turn off is sent to the MPS.

This turning on and off sequence can be see in the following figure.

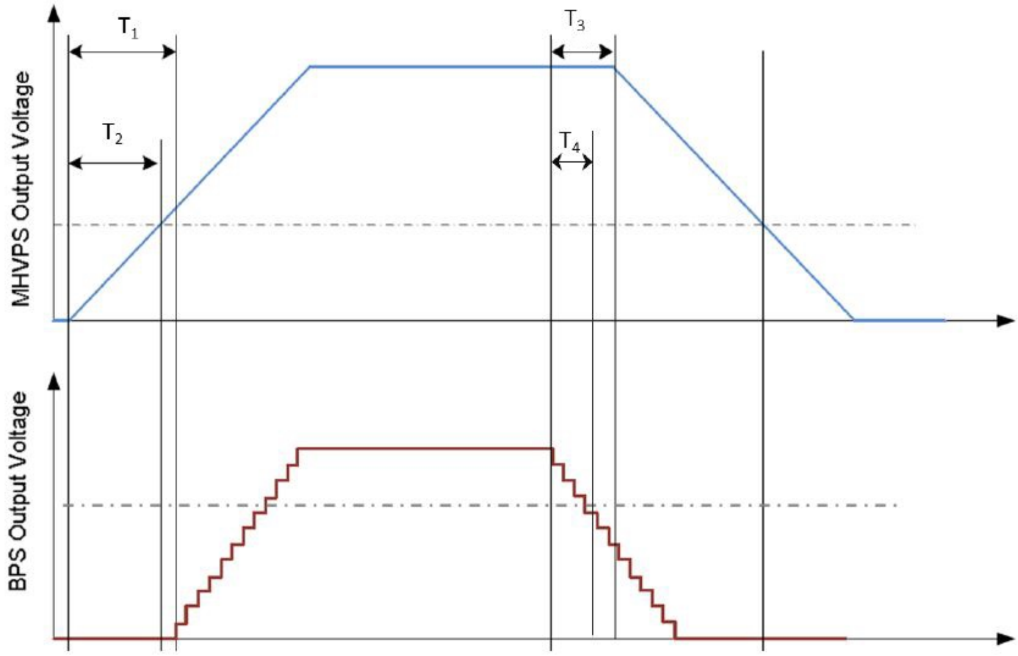

Figure 3.13: ON and OFF sequence of the HVPSs.
Source: [11]

T_2 represents the time it takes to the MPS voltage to go from zero to its voltage threshold. T_4 represents the time it takes to the BPS voltage to go from its reference voltage to its voltage threshold.

The Gyrotron and HVPSs can operate in two different ways:

- Normal operation: the gyrotron is switched on and off following a power reference request. The gyrotron switch on corresponds to the HVPS going from 0 V to a given reference. During the switching on and off sequences, the HVPSs follow a configurable ramp with ramp time from 100 μs to 1 ms.
- ON/OFF Modulation mode: the gyrotron is switched on and off following a square wave signal with maximum frequency of 5 kHz. Ramp up/down times are configurable and they are faster than the ones used for normal operation (a typical ramp time is 50 μs). In modulation mode, the duty cycle of the square wave (fraction of one period when the signal is active) is always 1/2.

Chapter 4

Design of the Control System

Once the operation principles and the components of the gyrotron have been presented and understood, the Control System that will coordinate the operation of all these systems and subsystems has to be created.

The gyrotron systems that will be installed in the ITER reactor have to be tested first. These tests are both for the components and the control system. This is performed in a Test Facility located in the *EPFL* University of Lausanne.

The control system used for the testing of the gyrotron has been baptised as the *FALCON* system. It is in charge of controlling the operation of the auxiliaries and the gyrotron in order to be able to generate a pulse in safe conditions, run tests on single or multiple auxiliaries, etc.

The model of that control system, designed using the MATLAB/SIMULINK tool, is described in this chapter, part per part.

This model allows operating the auxiliaries all together, in group or independently, satisfying both testing and operation mode purposes.

It is important to mention that not all the systems described in the previous section:

- The MOU is not presented as it is a passive system on which it is not necessary to act. It is a fixed mirror system that does not need to be controlled.
- The Arc detector system is not in the model as it belongs to the Interlock system, which is not fully integrated in this version of the model. This system will be integrated in future versions of the model when all the Interlock system for protection will be added.
- In the Test Facility there is no reactor or plasma. For this reason, the RF wave generated are sent to a spherical *Dummy Load* where the heat is distributed. This load has to be cooled, which is why there is an additional channel in the Cooling System that will cool this load. This cooling will depend on the length of the pulse, as it will be explained later.

The FALCON system model has two main parts:

- The High Voltage Power Supplies (HVPS), composed by:
  - The Main High Voltage Power Supply (or Main Power Supply (MPS)), which provides a difference of potential of approximately 50 kV between the cathode (where the electrons are extracted) and the collector (connected to the ground).
  - The Body Power Supply (BPS), which provides a difference of potential of approximately 30 kV between the cathode and the anode (where the output window is located) that allows accelerating the electrons from one point to the other.

- The Auxiliary Systems, composed by:
  - The Ion Pumps, powered by the Ion Pump Power Supplies (IPPS).
  - The Superconducting Magnets, powered by the Superconducting Magnets Power Supply (SCMPS), that is kept in superconducting conditions thanks to its cryogenic system (SCMCS powered by the Compressor).
  - The Oil Tank, in charge of insulating the electrodes of the electron gun and segments of HV cables connecting to the cathode.
  - The Filament, from where the electrons are extracted in order to generate the RF of the gyrotron, powered by the Cathode Filament Power Supply (CFPS).
  - The Collector DC Coils, in charge of decelerating the electrons once they are inside the collector, powered by the Collector DC Power Supply (CDCPS).
  - The Collector Sweeping Coils, that deviate the electrons to impact at different places of the collector's walls, powered by the Collector Sweeping Power Supply (CSWPS).
  - The Gun Coils, who are responsible of extracting the electrons from the filament and start driving them inside the cavity, powered by the Gun Coil Power Supply (GCPS).
  - The Vacuum System, responsible of keeping the vacuum between the transmission line, the Matching Optical Unit (MOU) and the gyrotron output.
  - The Cooling Water System (CWS), which is in charge of removing the heat from the collector, as it will heat up due to the impact of the electrons, and all the previously mentioned subsystems of the gyrotron.

In normal operation of the gyrotron, these two parts have to work together in a coordinated way in order to guarantee a correct operation of the device.

The model is composed by different blocks, state machines and subsystems that are interrelated in order to coordinate the operation of the FALCON system.

This integrated system can be divided into four main parts:

1. Mode selection and auxiliaries state checking: it is responsible of choosing the mode of operation of the gyrotron, selecting which auxiliaries will be active during the simulation and checking the state of each of the active ones, triggering an OK signal when they reach normal operation conditions.

2. Main State Machine: it is the heart of the model. It is in charge of coordinating the operation of the auxiliaries and the HVPSs in a given sequence. If there is any kind of problem or fault in any of the subsystems, it automatically shuts down all the other components for the protection of the whole system.

3. Auxiliaries block: this block contains all the auxiliaries that are part of the FALCON system (previously mentioned in page 43). It is in charge of the operation of all these auxiliaries, following the instructions sent by the Main State Machine and extracts the state of each one of these systems.

4. HVPS Operation and Control system: this part of the system works by coordinating several subsystems that receive the start signal from the Main State Machine and then follow a given sequence to turn on and off both the MPS and the BPS.

These four groups have to work in a correct and coordinated way in order to make sure that every part of the system is operating correctly and ensure that the system will have a fast protection response in case of having any failure or fault in any of its parts.

The full model, with the four blocks identified, can be seen in Figure 4.1. Each of these groups will be developed in details in the following sections of the document.

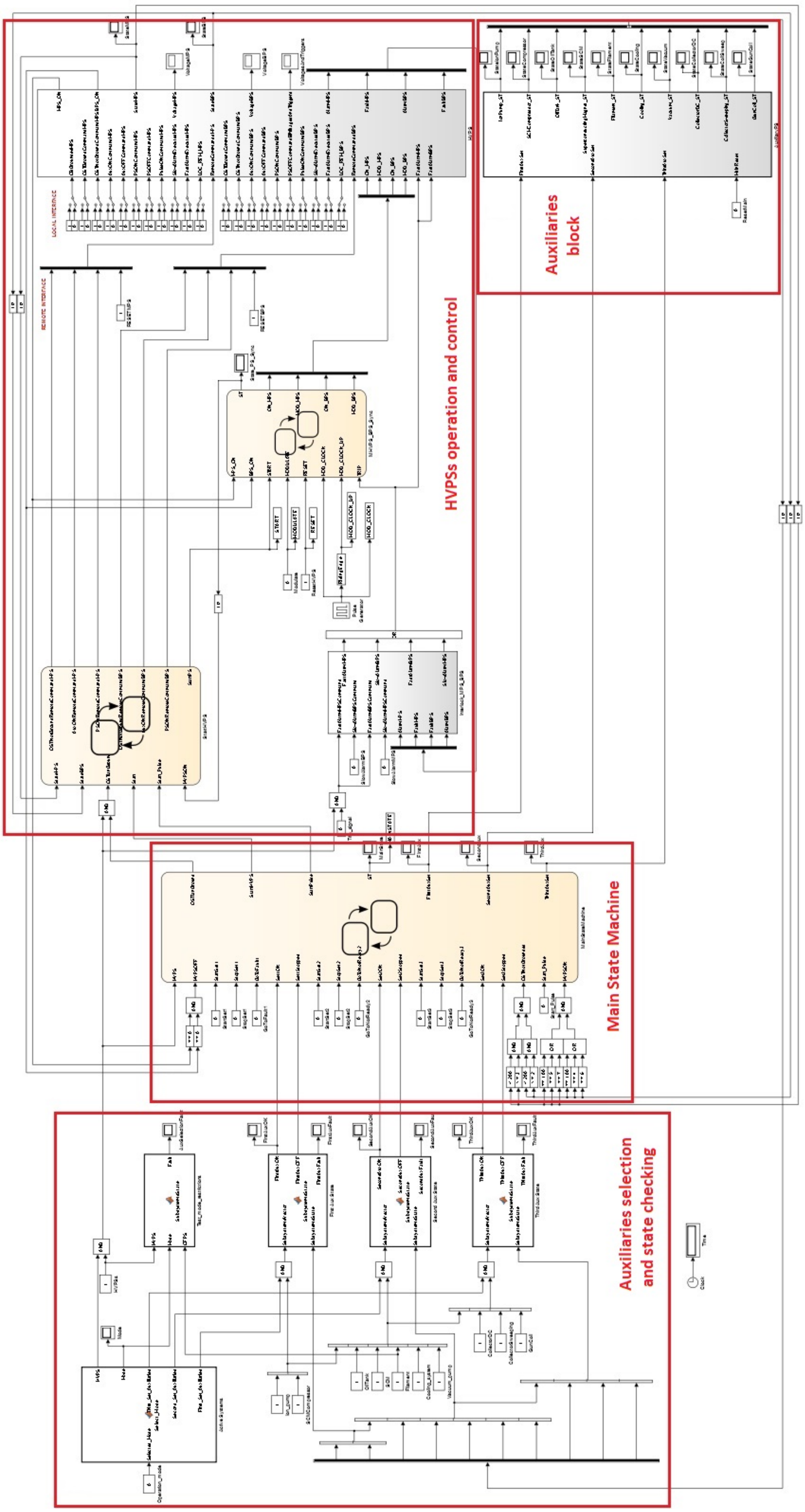

Figure 4.1: Global model of the FALCON system.
Source: MATLAB/SIMULINK

4.1 Mode selection and auxiliaries state checking

The first main block that composes the FALCON control system is the one in charge of selecting the mode of operation, which will determine which are the active auxiliaries, and checking the evolution of their state.

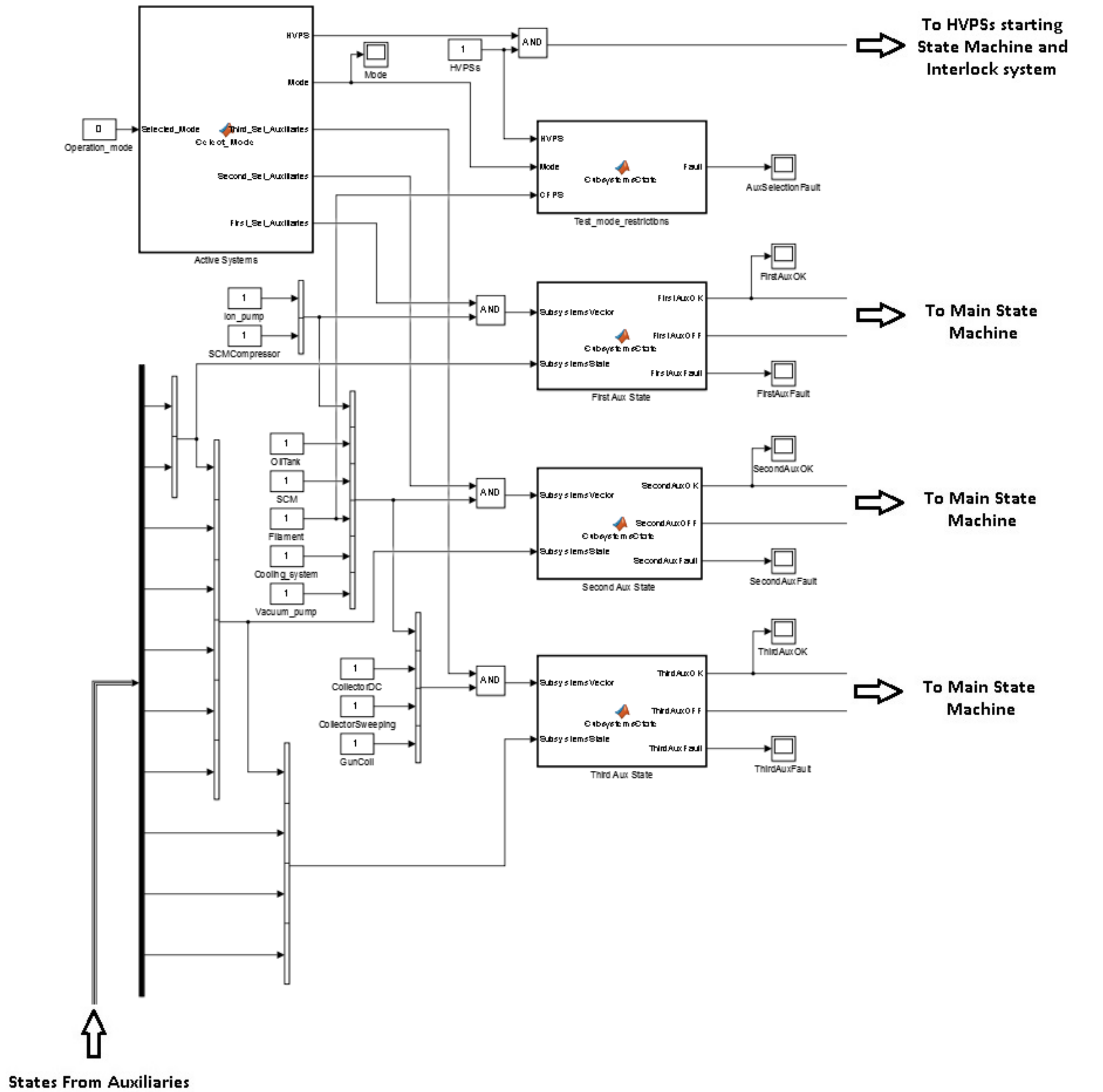

Figure 4.2: Mode selection and auxiliaries state checking.
Source: MATLAB/Simulink

This whole block receives as an input the state in which every auxiliary system is. Using the demultiplexor, the state of each auxiliary system is separated. For the operation of the gyrotron, a sequence has to be followed when turning on the auxiliaries. The sequence is the following:

- First set: in the first stage, two auxiliaries are turned on
  - The **Ion Pumps** start operating in order to generate vacuum inside the gyrotron. This system will continue working all along the operation of the gyrotron to make sure at every moment that the vacuum is kept inside the collector, to avoid interactions of the electron beam or the RF with any particle that could be inside the tube.

  - The **Superconducting Magnets Cryogenic System** (SCMCS) is turned on in order to start cooling the superconducting magnets to make sure they are in superconducting conditions. This system will be operating continuously to try to avoid that the temperature of the superconducting magnets reaches the quenching point.

  These two systems are essential for the correct operation of the gyrotron. However, both of them are slow, which is why they are the first ones to be started and they will be needed permanently (even when the gyrotron is not operating). They guarantee the vacuum inside the gyrotron tube and keep all the superconducting coils at the required temperature.

- Second set: once the auxiliaries from the first set have reached normal operation conditions, the second set of auxiliaries is started
  - The **Oil Tank** is in charge of insulating the electrodes of the gyrotron electron gun and segments of HV cables connecting to the cathode. The control system is only monitoring the oil flow, which is indicated by a sensor.
  - The **Superconducting Magnets** have a key role for the operation of the gyrotron. The magnetic field that they generate determines de RF frequency and allows coupling the electron beam with the cavity oscillation inside the gyrotron tube. For this reason, the output current of the SCMPS has to be controlled according to the gyrotron operation.
  - The **Filament** starts being heated by Joule effect, powered by the CFPS. It is a slow process before it reaches nominal current, which can be controlled, and temperature for the extraction of electrons.
  - The **Cooling Water System** is turned on to start cooling all the auxiliary PSs and other areas like the collector of the gyrotron, that will heat up a lot once the gyrotron starts operating due to the impact of the electrons deviated by the Collector Sweeping Coils. The Cooling System is composed by different circuits in charge of the cooling of different parts. These subsystems need to be controlled and checked as well.
    * Auxiliaries Cooling: it is responsible of cooling all the auxiliary systems (to prevent the PSs from heating too much) and other components of the gyrotron such as the output window, the reflecting mirrors, the cavity, the transmission line, etc. It includes an extra system that is responsible of cleaning the water (recirculation from main tank to a smaller tank equipped with UV light).
    * Collector Cooling: it is responsible of extracting the heat from the collector walls, that will heat up a lot due to the impingement of the accelerated electrons (it could need flow rates up to 3000 L/min).
    * Dummy Load Cooling: while operating the gyrotron, the dummy load will heat up a lot due to the interaction with the output RF. Depending on the mode of operation (Short or Long Pulse); the necessary cooling will be higher or lower.
    * Operation of the Primary Valve: this valve is the entry point of water inside all the previously mentioned circuits. This valve needs to be controlled depending on the needs of every cooling subsystem.
  - The **Vacuum System** is the one responsible of keeping the vacuum in the path of the RF after exiting the gyrotron output window. This means that is has to keep the vacuum inside the MOU and the transmission line to avoid any interaction with particles.

- Third set: when all the auxiliaries of the first and second sets are working in normal conditions, the third and last set of auxiliaries is started

- The **Collector DC coils** are used to decelerate the electrons when entering in the collector, after the output window. This reduces the energy of the electrons and thus the heat that they will transmit to the collector walls when impinging.
- The **Collector Sweeping coils** are responsible of diverting the electrons arriving inside the collector to change their impact point on the walls so that the heat load is distributed along the whole collector. This is done by generating a saw-shaped current output.
- The **Gun Coil** is responsible of extracting the electrons from the Filament. This is done by applying a strong magnetic field towards the Filament, attracting the electrons that will eventually get detached from it. These are the electrons that will be accelerated and will generate the output RF of the gyrotron.

The gyrotron can be operated in 6 different modes. Depending on the selected mode, the active auxiliaries are different.

Table 4.1: Operational scenarios and Subsystems involved

Operational scenario	**1. Auxiliaries test**	**2. Gyrotron operation on air**	**3. Very short pulse load**	**4. Short pulse load**	**5. Gyrotron conditioning**	**6. Normal operation**
Subsystems involved	From one to all subsystems *	- IPPS - SCMCS - Oil tank - SCMPS - CFPS - CWS - GCPS - HVPS	- IPPS - SCMCS - Oil tank - SCMPS - CFPS - CWS - Vacuum system - GCPS - HVPS	- IPPS - SCMCS - Oil tank - SCMPS - CFPS - CWS - Vacuum system - GCPS - HVPS	- IPPS - SCMCS - Oil tank - SCMPS - CFPS - CWS - Vacuum system - CDCPS - CSWPS - GCPS - HVPS	- IPPS - SCMCS - Oil tank - SCMPS - CFPS - CWS - Vacuum system - CDCPS - CSWPS - GCPS - HVPS

* CFPS and HVPS cannot be active at the same time in test mode

For testing purposes (Auxiliaries test mode), the user can decide which of these auxiliaries he wants to operate. This can be done by selecting the components the user is interested to test (before starting the operation), setting the Constant values in the blocks to '1' (Active Component) or '0' (Inactive Component). If a component is declared as Inactive, it will not be operable from the model (no possible Remote action on the component). This option can be used when one of the auxiliaries is operated locally by another operator. The HVPSs are also selectable; they have their own Constant block so that the user can define them either as active or inactive. It has to be mentioned that they are treated as a pack (MPS and BPS can only be both active or both inactive). However, there is a constraint that has to be respected: the HVPS and the Filament PS cannot be operated together. This is checked in the model by the first *MATLAB Function* block called *Test_mode_restrictions* (top-centre on Figure 4.2). In case of being operated in this mode and having set both the HVPS and the Filament PS as active,this block will indicate that there is a fault, which, in future versions of the model, could actuate on the Main State Machine and unable its start.

The other modes are used for different purposes and have different lengths:

- Gyrotron operation on air: the gyrotron is operated in the air at very low power, the RF window sends the RF wave in air. It is used for measurements of the mode and shape of the RF created by the gyrotron. A way of measuring the mode is by shooting at a thermal sheet of paper that keeps the footprint of the pulse ($t \leq 10\,ms$).

- Very short pulse load: the gyrotron RF window is connected to the MOU. At the output of the MOU there is a very small Dummy Load to take some measurements. The subsystems linked to the collector (CDCPS and CSWPS) are not used here because the pulse is so short that it is not necessary to activate them to distribute the heat load ($10\,ms \leq t \leq 100\,ms$).
- Short pulse load: the Dummy Load is bigger than the previous one (same size as the one that will be used for the normal operation) and has many different measurements instruments inside. After a very short pulse, the evolution of the temperature is measured until it gets back to ambient temperature. The amount of energy generated can be calculated by integrating the shape of the temperature curve. The systems linked to the collector (CDCPS and CSWPS) are not used here either as the pulse is too short ($100\,ms \leq t \leq 1\,s$).
- Gyrotron conditioning: this mode is used to 'warm up' the gyrotron before starting the normal operation: it consists in short pulses of different lengths (up to 100 ms) and power (up to 100 %) to make sure that everything works correctly and remove any possible particle from inside the gyrotron or the MOU using the vacuum pumps. The current stabilization of the filament PS for the pulse is also done in this mode. If the gyrotron has not been operated for a certain number of hours, several small pulses have to be made in order to have the system in the adequate conditions. In this mode all the subsystems and protections are active. This mode uses the normal Dummy Load at the exit of the MOU. This load is highly cooled and only measures the input and output temperature of the cooling water to determine the energy deposited.
- Normal operation: After having done the Gyrotron conditioning, the normal mode of operation can be used, which can do last up to 1 hour.

If the system is being operated in any mode except the Auxiliaries test, it is mandatory that all the Constant values in the blocks are set to '1', so that the *MATLAB Function* block called *Active Subsystems* (top-left on Figure 4.2) can directly send the list of active components depending on the selected mode. The operator can only set the mode, the list of active subsystems is automatically determined (except in test mode).

The three *MATLAB Function* blocks that can be seen in Figure 4.2 are the ones in charge of checking the state of only the Active Components. The first block takes into account the first set of auxiliaries; the second one considers the first and second sets and finally, the third block checks the states of all the three sets of auxiliaries. For each block, if all the active auxiliaries considered are in steady state (considered as state '100'), the *FirstAuxOK* (or *SecondAuxOK* or *ThirdAuxOK*) output signal becomes '1', and otherwise, it is '0'. If at any point, during the operation of the system, any auxiliary exits its normal operation state, this output will be set back to '0'. Displays have been connected to these three signals so that the user can visualize them easily. If any of the auxiliaries considered for a block has a fault (identified as state '200'), the *FirstAuxFault* (or *SecondAuxFault* or *ThirdAuxFault*) signal goes to '1'. When *XXXAuxOK* is zero, it only indicates that all the auxiliaries are not in normal operation state, without knowing in which specific state it is. These *XXXAuxFault* output signals are created in order to be able to identify when any of the auxiliaries is in fault state. The *FirstAuxOFF* (or *SecondAuxOFF* or *ThirdAuxOFF*) output signals are the ones responsible of indicating if the output power of all the auxiliaries from the corresponding set is off.

Both the *XXXAuxOK* and *XXXAuxOFF* signals are sent and used as inputs for the Main State Machine. The *XXXAuxFault* are not used at this state of the model as they belong to the Interlock System, which is a higher level system that has not been included yet in the model [1].

[1] See Future steps section.

4.2 Main State Machine

The Main State Machine is the system responsible of coordinating the global operation of the FALCON system at the highest level. It is the one that controls the initialization and shutdown of the auxiliaries, following a sequence organized in sets (the same sets and in the same order as in the previous section 4.1 of the document), and the HVPSs.

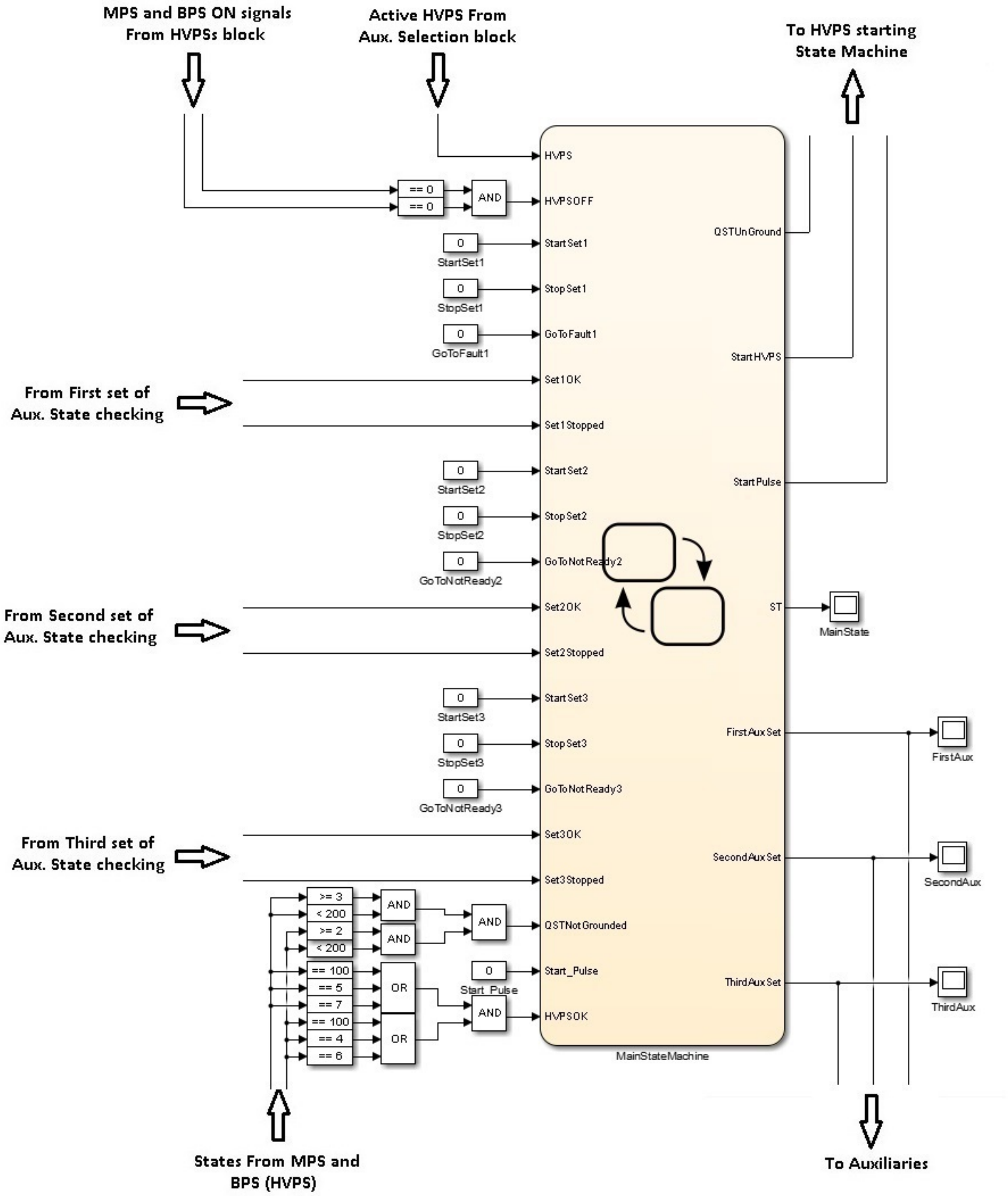

Figure 4.3: Model of the Main State Machine signals.
Source: MATLAB/SIMULINK

It receives several input signals that will determine the evolution of the whole system:

- The *HVPS* signal, which indicates whether the HVPSs are active or not in the simulation. This signal will be helpful to know if it is necessary of not to check the input signals related with the operation of the HVPSs or not. In case of not using the HVPSs in the simulation, there will be no need to check any of the signals from the HVPSs as they will not be operated. In case of including the HVPSs in the simulation, then all these input signals are considered again.

- The *HVPSOFF* signal, which indicates if the voltages of the HVPSs are ON or OFF.

- The *Set1OK / Set2OK / Set3OK* signals that indicate if the auxiliaries from each of the three sets are working in normal operation conditions or not.

- The *Set1Stopped / Set2Stopped/ Set3Stopped* that indicate if the auxiliaries from each of the three sets are OFF or not.

- The *StartSet1 / StartSet2 / StartSet3* commands that will initiate each of the sets of auxiliaries.

- The *StopSet1 / StopSet2 / StopSet3* commands that will stop the operation of the auxiliaries from each set.

- The *GoToFault1 / GoToNotReady2 / GoToNotReady3* commands that, in case of having any kind of problem while initiating any of the three sets of auxiliaries, will allow moving to a different state that will give the option of restarting the corresponding auxiliaries, or stopping the whole set.

- The *Start_Pulse* command that will switch on or off the output of the HVPSs in order to start or stop the pulse.

- The *QSTNotGrounded* signal that indicates if the MPS and the BPS are still connected to the ground or not. The ground connection is disconnected in the MPS and the BPS from states 3 and 2 respectively, corresponding to the *QSTNotGrounded* state. This is lost in the alarm states of each of the HVPSs, corresponding to the states 200, 201, 300 and 301 (see *Appendix A.1* and *A.2*). This means that the QSTNotGrounded signal will be '1' if $3 \leq State_{MPS} < 200$ and $2 \leq State_{BPS} < 200$.

- The *HVPSOK* signal, which indicates if the HVPSs (both MPS and BPS) are ready and/or operating or not. The HVPSs are OK when they are in states 5 (4 for BPS), corresponding to Idle state; 7 (6 for BPS), corresponding to Transition state; or 100, corresponding to Normal Operation state (see *Appendix A.1* and *A.2*).

These different input signals are used for the transitions inside the Main State Machine, which can be seen in Figure 4.4 .

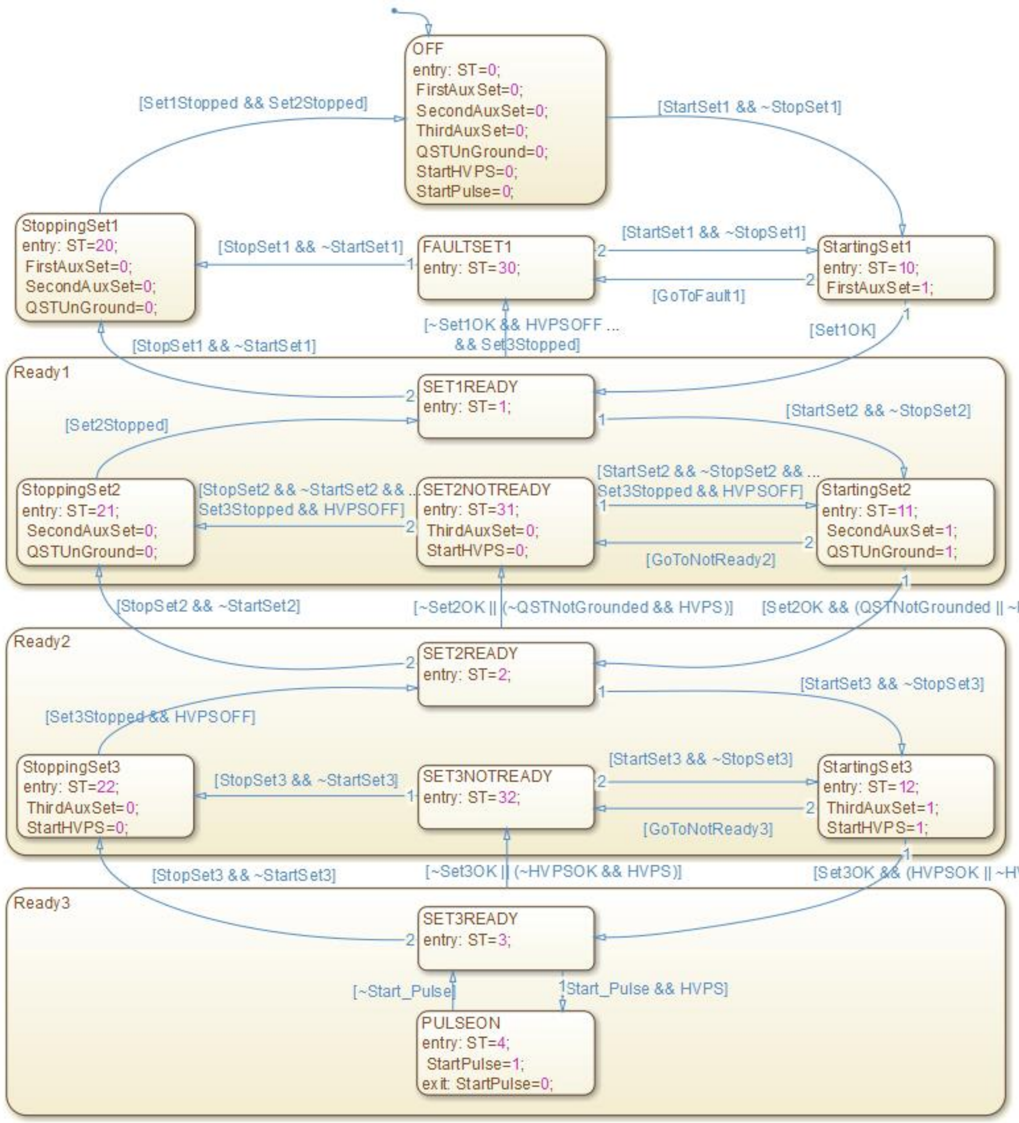

Figure 4.4: Main State Machine.
Source: MATLAB/SIMULINK

When the model is started, the Main State Machine is in OFF state. In this state, all the output signals are at zero. If the *StartSet1* command is set to '1', the state machine moves to StartingSet1 state, where the auxiliaries from the first set (SCM Compressor and IPPS) are started using the *FirstAuxSet* output signal. Some auxiliaries, like the SCMPS, the CDCPS or the GCPS need to be initialized in order to be configured and to set the reference values before being able to turn them on. This initialization is also done in this stage. Once both the IPPS and SCM Compressor auxiliaries reach normal operating conditions, the *Set1OK* input signal will become '1', allowing the transition to SET1READY state.

In this state, if the *StartSet2* command is received, the system moves to StartingSet2 and the second set of auxiliaries is started with the *SecondAuxSet* output signal. In this same state, the ground connection of both the MPS and the BPS will be disconnected using the output command *QSTUnGround*. When the SCMPS, the CFPS, the Cooling System and the Vacuum system reach their steady state, the signal *Set2OK* becomes '1'. At the same time, the system checks if the ground connection of both HVPSs has been disconnected. This is done through the input signal *QSTNotGrounded*, which will become '1' when both power supplies are not grounded anymore. When both signals are high, the system can move to state SET2READY.

Then, if the *StartSet3* command is sent, the state machine moves to StartingSet3, where the remaining auxiliaries are turned on (CDCPS, CSWPS and GCPS) with the *ThirdAuxSet* output signal. In this same state, the *StartHVPS* output signal is sent to the Start HVPSs state machine. This signal will allow both HVPSs to move up to the Idle state (state 5 for MPS and 4 for BPS). When the HVPSs reach this state, the *HVPSOK* signal will be generated and when all the auxiliaries from the third set are working in normal conditions, the *Set3OK* signal will change to '1'. When both signals are high, the state machine moves to SET3READY.

At this point, all the auxiliaries are working in normal conditions and the HVPSs are ready to start a pulse. This can be done by sending the *Start_Pulse* command to the HVPSs, which will turn on the output voltage of both the MPS and the BPS, starting the production of RF power. The state machine will then move from SET3READY to PULSEON.

The pulse can be stopped at any moment by putting the *Start_Pulse* command back to low ('0').

During the starting of any of the sets, if there is any problem with any of them or the starting is taking too long, the *GoToFault1* (while starting set 1) / *GoToNotReady2* (while starting set 2) / *GoToNotReady3* (while starting set 3) commands can be sent to make the state machine move to FAULTSET1 / SET2NOTREADY / SET3NOTREADY respectively. From this new state, the user can decide if stopping the auxiliaries and actions from this stage or trying to restart them (using the *StopSetX* or *StartSetX* commands).

It is important to mention that the input signals *SetXOK* check the state of their corresponding set of auxiliaries but also the sets that were initiated before (*Set2OK* checks auxiliaries from sets 1 and 2; *Set3OK* checks auxiliaries from sets 1, 2 and 3) so that, if any auxiliary from a previous state fails, the system can move back in the state machine until reaching the corresponding state.

For example, if during a pulse (system in PULSEON state) there is a fault in the Cooling system (which belongs to set 2), the *Set3OK* will become '0', moving from PULSEON to SET3NOTREADY and then from SET3NOTREADY to SET2NOTREADY as *Set2OK* will also be '0'. With the first transition, the pulse will be stopped (MPS and BPS will go from SteadyState back to Idle state) and, with the second transition, all the components of the third set will be automatically turned off and the HVPSs will go back to QSTGrounded state. When reaching this state, the user can decide if turning off the second set of auxiliaries as well or to restart it if the fault has been solved.

If once the second set of auxiliaries has been started there is a fault in any of the auxiliaries from the first set, the action is a bit different: due to the fault in set 1, the signal *Set1OK* will get back to '0', this will make the system move to FAULTSET1. In this state, the auxiliaries from the second set are not turned off as they can operate if one from the first set fails. Moreover, some of the auxiliaries from the second set are slow to start (the cathode filament for instance takes hours before reaching the operating temperature). For this reason, it is not wanted to stop the auxiliaries from the second set automatically every time there is an incident in the first set. If there is a real problem in the first set, then the user will send the command *StopSet1*. If the stop command is sent, then both the first and the second set will be stopped and both HVPSs connections will be grounded again. This is done in order to avoid that at false error signal from the auxiliaries of the first set make the entire second set stop automatically. It will only be necessary to stop everything if there is a real problem in the first set.

Stopping automatically the auxiliaries from the third set is not a problem as all of them reach the normal operation conditions in a few seconds after being started.

The turning off sequence is right the opposite, from the PULSEON state, the commands to stop are sent: first *Start_Pulse* has to be set back to '0', then the *StopSet3* command and so on until moving back to OFF state.

In general, the auxiliaries from the first set will always be on (unless they fail or any special circumstance requires to shut them down), which means that most of the time, for both pulses or testing purposes, the system will start from SET1READY state.

Sending any command in a moment when they are not a part of the transitions to exit the state in which the system is will have no effect at all. For example, sending the *StopSet1* command during a pulse (PULSEON state) will not make the pulse stop and the state machine move to another state. Each command will allow a transition to a new state only in the states where it can be used.

4.3 Auxiliaries block

The auxiliaries' initialization is controlled by the Main State Machine, which sends the *XXXAuxSet* signal in order to start the different set of auxiliaries. These signals arrive to the auxiliaries' block that can be seen in Figure 4.5.

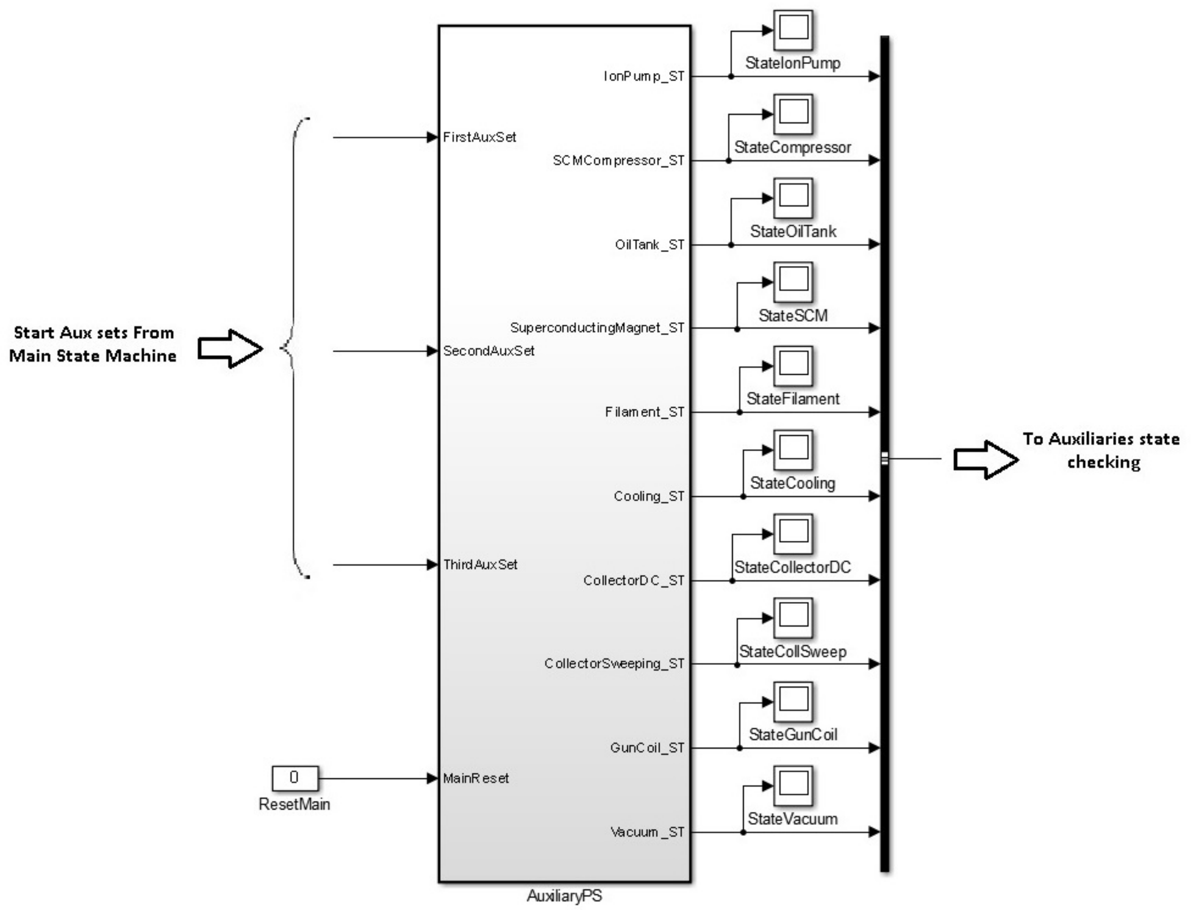

Figure 4.5: Model of the Auxiliaries block.
Source: MATLAB/Simulink

As inputs, the block receives the starting signal for each set of auxiliaries from the Main State Machine and the main *Reset* signal, sent by user to be able to reset all the auxiliary systems in case of fault or malfunction. All the different auxiliaries' models are inside the *AuxiliaryPS* block, whose output is the state of each one of them.

These states, which can be seen during the simulation in each of the displays, are sent all together to and treated by the Auxiliaries state checking (see Mode selection and auxiliaries state checking section).

The content of the *AuxiliaryPS* block can be seen in the following figure.

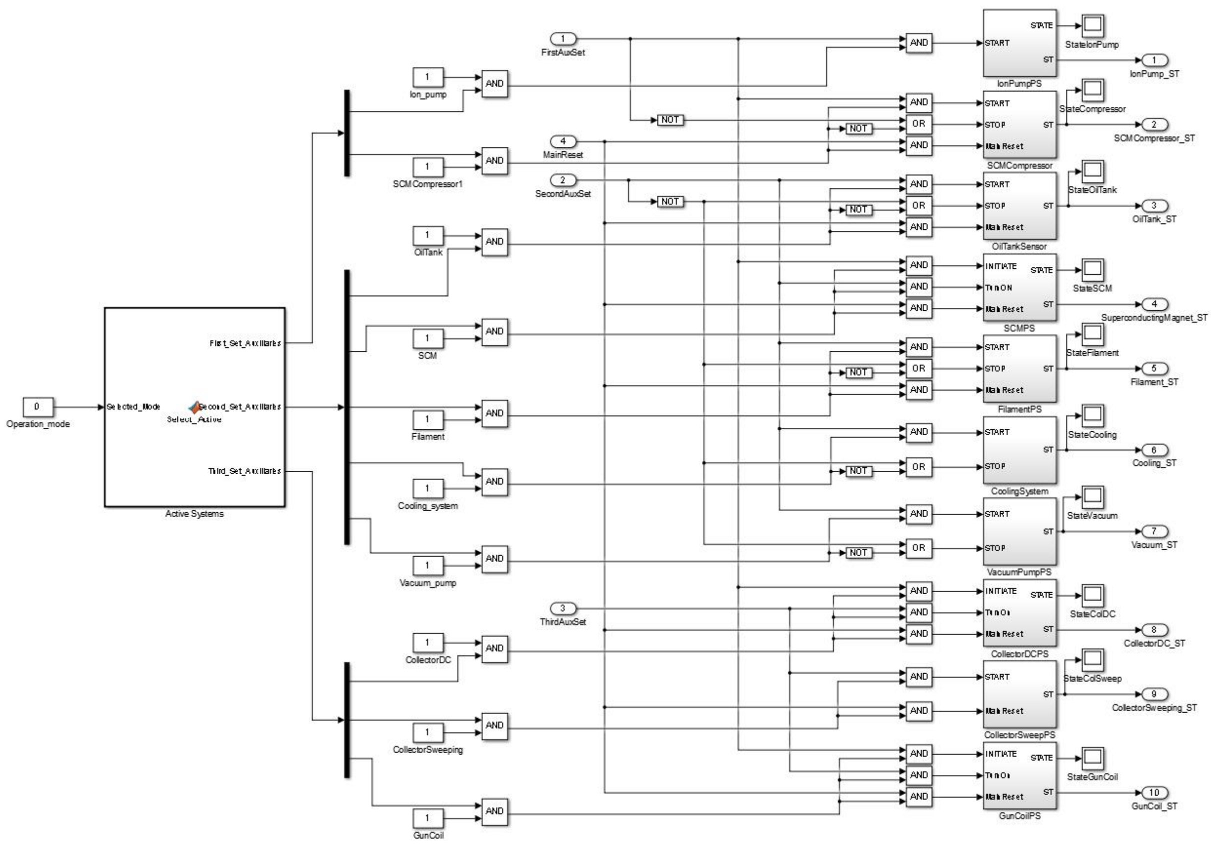

Figure 4.6: Model of the Auxiliaries operation and control.
Source: MATLAB/SIMULINK

Each of the different auxiliaries is started by its corresponding start signal (depending on the set it belongs to) and, as it has been mentioned in the previous section, some auxiliaries (SCMPS, Collector DC PS or Gun Coil PS) have an extra *INITIATE* input because they need to be initiated first (to configure them) and then started when output power is required. The initialization is done at the same time as the first set of auxiliaries starts and is only necessary for the first time they are operated as those parameters are saved inside the memory of the power supply. If needed, these parameters can be modified by the operator in the future at any moment.

The four input signals to Start/Stop or Reset all the different auxiliaries are present in Figure 4.6. The same *MATLAB Function* block described in section 4.1 to set the mode of operation can be found on the left side. There is also a Constant value block for each auxiliary. Both blocks must have the same mode and value as the ones in the first section, in order to avoid non-required auxiliaries to be operated during the simulation. Each one of the different blocks that can be seen contains the model and state machine of a different auxiliary system.

A special mention has to be made about the Cooling System block, which is composed of several subsystems, as it can be seen in Figure 4.7.

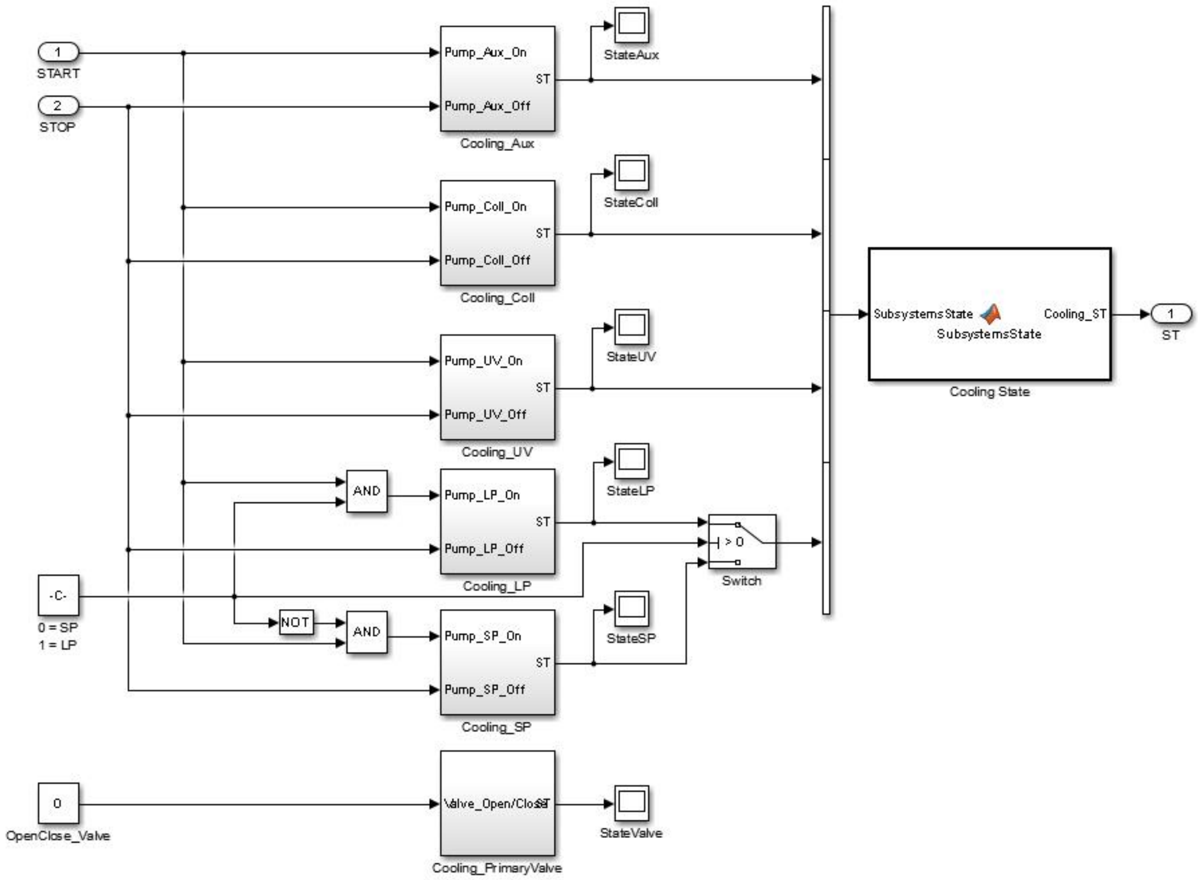

Figure 4.7: Cooling system components.
Source: MATLAB/Simulink

The first Constant block at the bottom-left part is a parameter fixed by the user, deciding whether the simulation will be a Short Pulse (SP) or a Long Pulse (LP). The length of the pulse changes the amount of cooling needed to keep the Dummy Load in the required range of temperatures. Depending on that, the Short Pulse Cooling or the Long Pulse Cooling will be used.

The Primary Valve of the cooling system works independently, which is why it is not connected to the START/STOP signals. Instead, there is a Constant block that allows opening or closing it when needed.

The models of the auxiliaries have been elaborated after a deep study and understanding of the technical documentation of the power source of each auxiliary provided by their manufacturer[2]. These documents allow understanding the operation of each auxiliary as well as the available input and output signals that can be controlled and measured. The outputs, as mentioned previously, are the state of each auxiliary, which is obtained from each of their own state machine.

[2] References [13], [14] [15] and [16] are some of the documents that have been used to design the models of the auxiliaries.

4.4 HVPS Operation and Control system

The HVPSs operation and control system is the most complex part of the simulator. For the control of both the Main Power Supply and the Body Power Supply, there are several different blocks and state machines:

1. The **Start HVPSs** state machine is in charge of initializing both the MPS and the BPS depending on their own state, after all the auxiliaries are ready and sending the necessary remote commands for the HVPSs to progress in their own state machines, up to the Idle state.

2. The **Interlock System** is the one in charge of detecting if a fault signal is generated either internally (due to a fault or an alarm in the MPS or the BPS) or externally (due to a fault in another part of the global system, e.g. in an auxiliary system) and trip the HVPSs if necessary.

3. The **HVPSs Synchronization** state machine is the one responsible of sending the ON/OFF commands to the HVPSs in the right sequence. It also integrates the use of a modulation mode for the HVPSs. This state machine uses information from the two previous subsystems as input signals.

4. The **HVPSs Main Block** contains the state machines of the MPS and the BPS. The voltage generated by both can also be seen inside this block. It is the central part of the HVPSs system and it receives and sends signals to the three previous systems.

As it can be seen, all four subsystems are fully integrated and dependent of each other, each of them having their specific functions, which are vital for the operation of the HVPSs.

This huge block also interacts with the rest of the global system:

- It receives the three different start signals from the Main State Machine, which also depend on the auxiliaries operation. These different signals will make the state of the HVPSs evolve progressively from being totally off to producing an RF pulse through steps.

- It sends the MPS and BPS states and voltage signals to the Main State Machine, in order to generate the *HVPSOK* and *HVPSOFF* signals.

The HVPSs simulator gives the option of operating the HVPSs remotely or locally. This can be done by changing a switch that indicates in which mode is each HVPS. For Local mode, there is a large set of switches in the HVPSs Main Block that are sufficient to fully control the MPS and the BPS and that can be used to make them evolve through their state machines. The subsystems 1, 2 and 3 are only useful when the HVPSs are working in Remote mode.

There is a Constant block called *HVPSs* that allows selecting if the High Voltage Power Supplies are going to be operated or not in the simulation (just as for the auxiliaries).

The model of this system and its separation in the different subsystems can be seen in Figure 4.8.

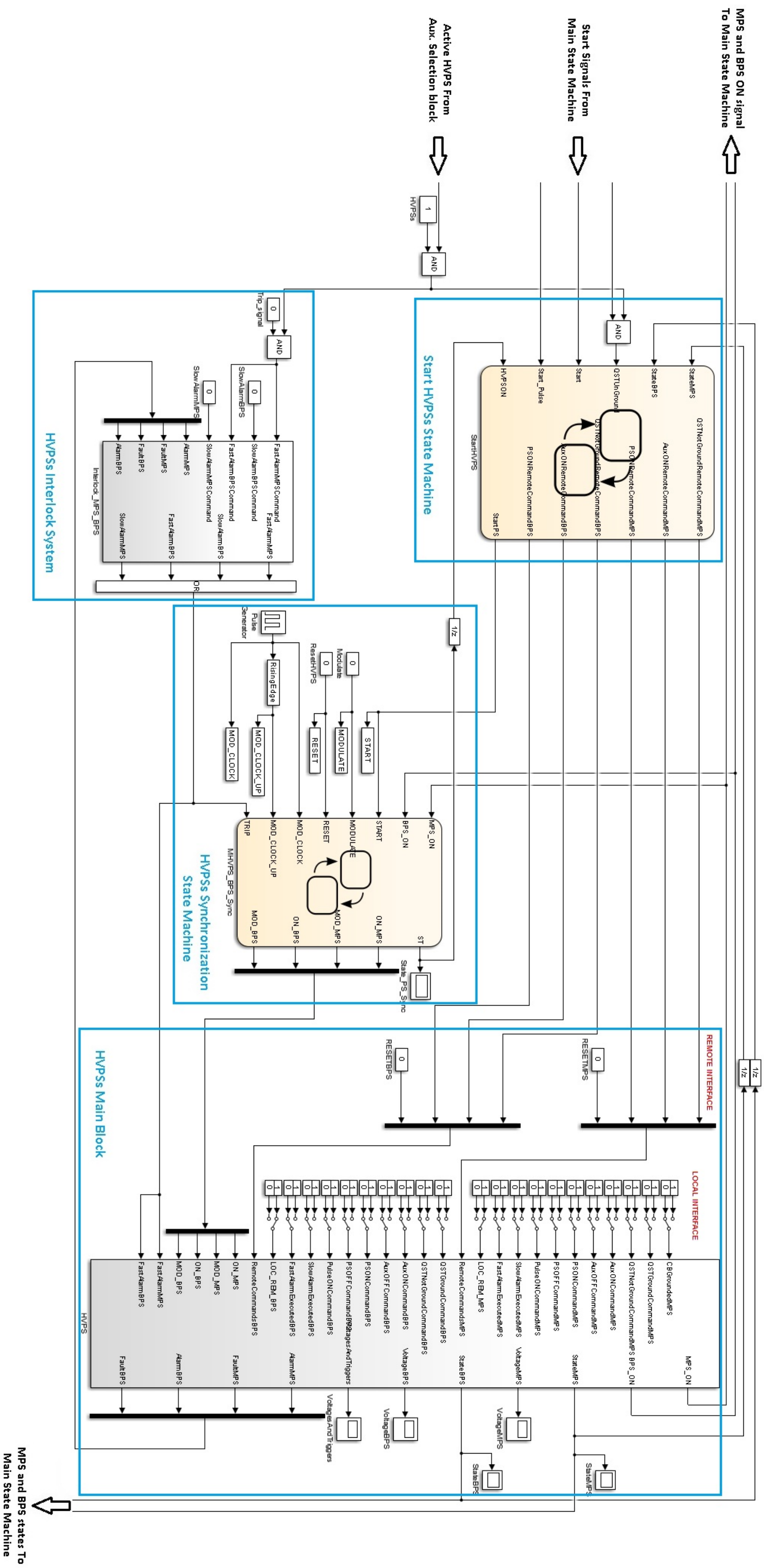

Figure 4.8: Model of the HVPSs operation and control block.
Source: MATLAB/SIMULINK

4.4.1 Start HVPSs

As the Main State Machine evolves, the user sends the commands to start the different sets of auxiliaries, some signals are also sent to the HVPSs in order to get them ready for operation. This first block is the one that will allow bringing both the MPS and BPS from their corresponding OFF state to their Idle state (see *Appendix A.1* and *A.2*), where all the parameters have been set, and initiating the HVPSs Synchronization state machine, which will be in charge of coordinating the operation of the HVPSs during the pulse.

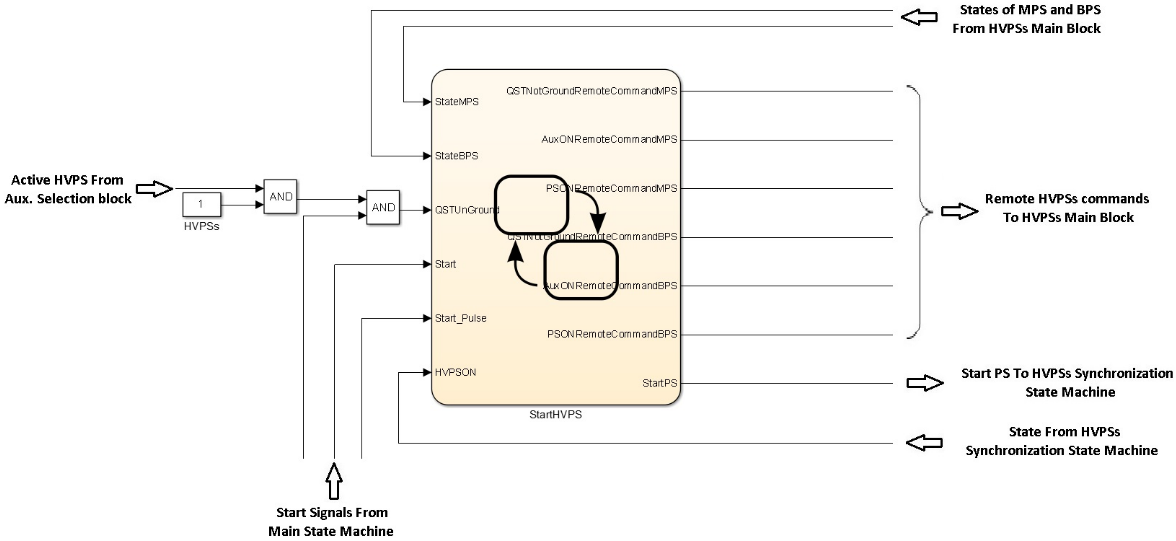

Figure 4.9: Model of the Start HVPSs state machine.
Source: MATLAB/SIMULINK

This state machine has different input signals

- The *QSTUnGround* command from the Main State Machine, which is sent at the same time the second set of auxiliaries is started (or stopped). This command will allow disconnecting (during the turning on phase) or connecting (in the shutdown phase) the ground connection of both the MPS and the BPS. If the user decides that the HVPSs will not be used in the simulation (HVPSs Constant block set to '0'), the *QSTUnGround* command will have no effect on the state machine and nor will any of the other signals sent from the Main State Machine as this is the one that initializes the whole HVPSs control and operation block.

- The *Start* command from the Main State Machine, sent as the third set of auxiliaries is started, will allow bringing the HVPSs up to their Idle state.

- The *Start_Pulse* command, coming directly from the Main State Machine when the user decides to start producing the RF once all the systems are ready, will be the one that starts the HVPSs Synchronization state machine.

- The states of the MPS and the BPS, coming from the HVPSs Main Block, which allow controlling in which step of their own states machines they are. Depending on their states, the output signals will change, activating different remote commands.

- The state of the HVPSs Synchronization State Machine, which will allow knowing when the voltages of the MPS and BPS are ON or OFF.

The state machine of the initialization of the HVPSs can be seen in Figure 4.10.

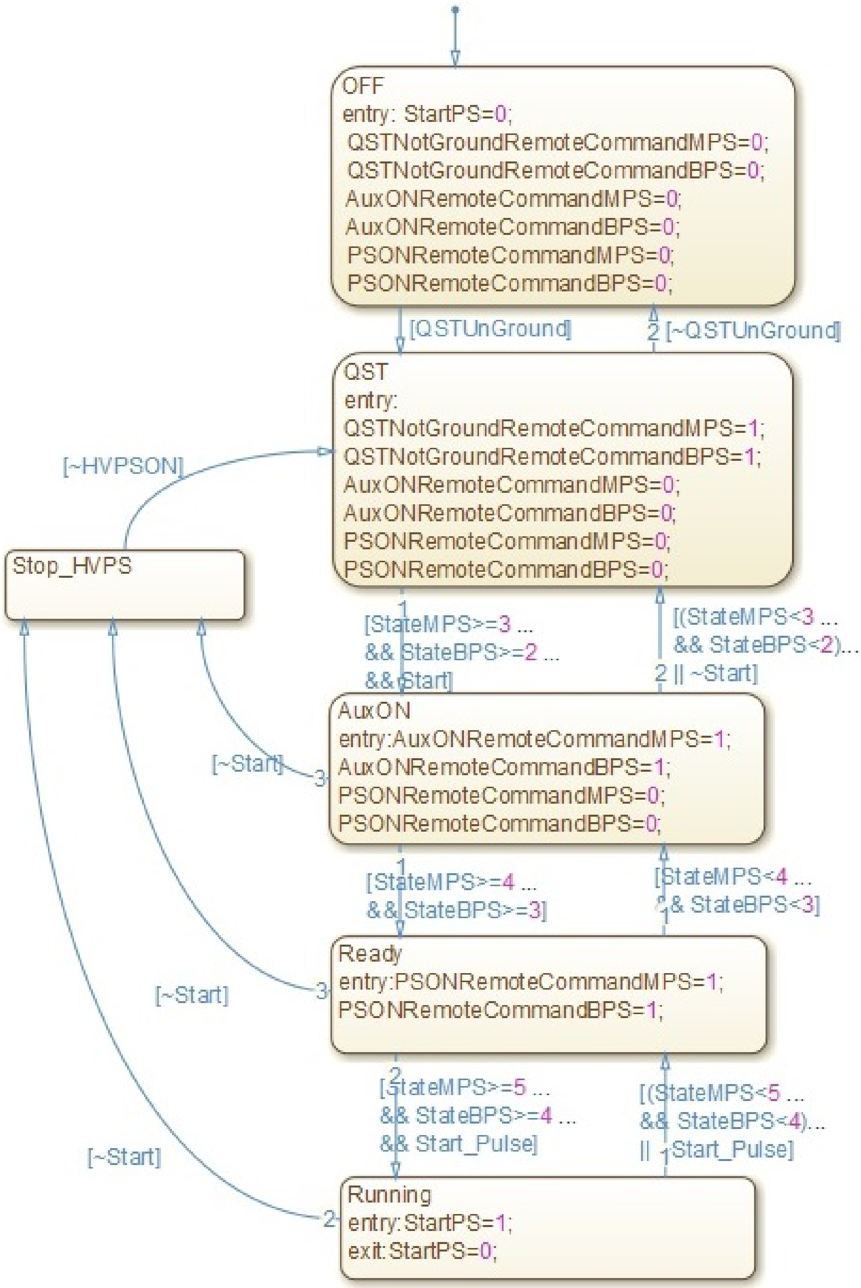

Figure 4.10: Start HVPSs state machine.
Source: MATLAB/SIMULINK

As it can be seen, after receiving the *QSTUnGround* command, the state machine will move from OFF to QST state, where the remote commands to disconnect the ground connection of the MPS and the BPS will be sent.

When the *Start* signal is received, the state machine will move from QST to AuxON, indicating that the auxiliaries are ready (except the ones from the third set, which are being started at the same time). This state and the following one (Ready) will bring the MPS and the BPS up to their Idle state, where both will be ready to start operating, just waiting for the signal to turn on their output power. All these remote commands are sent directly to the HVPSs Main Block.

The system will remain in this state until the user sends the command to start a pulse and generate RF. At this moment, the state machine will move to Running state, where the last output signal, *StartPS*, is sent to the HVPSs Synchronization state machine to set the turning ON/OFF sequences of the MPS and the BPS.

There are two ways of stopping the HVPSs:

- The progressive shutdown, which is the one that will be used if everything works correctly, will step by step bring the state machine back as the user sends the requests to stop the pulse and the different sets of auxiliaries one after the others.
- The fast shutdown. If at any moment there is a fault in the first or the second sets of auxiliaries during a pulse, the *Start* signal will become '0' and the state machine will move to STOP_HVPS. The state machine will stay there until receiving the signal that both power supplies are off ($HVPSON = 0$). When receiving that signal, the state machine goes back to the QST state. This alternative path is used for fast actuation on the HVPSs.

4.4.2 Interlock System

The Interlock system is the part of the HVPS control that shuts down both power supplies in case of having any Alarm or Fault, which can come from the HVPSs themselves or from other parts of the system (e.g. a fault in an auxiliary system). In the current model, the trip signal can be injected manually by the user as an external alarm signal or triggered by alarms and faults coming from the HVPSs Main Block.

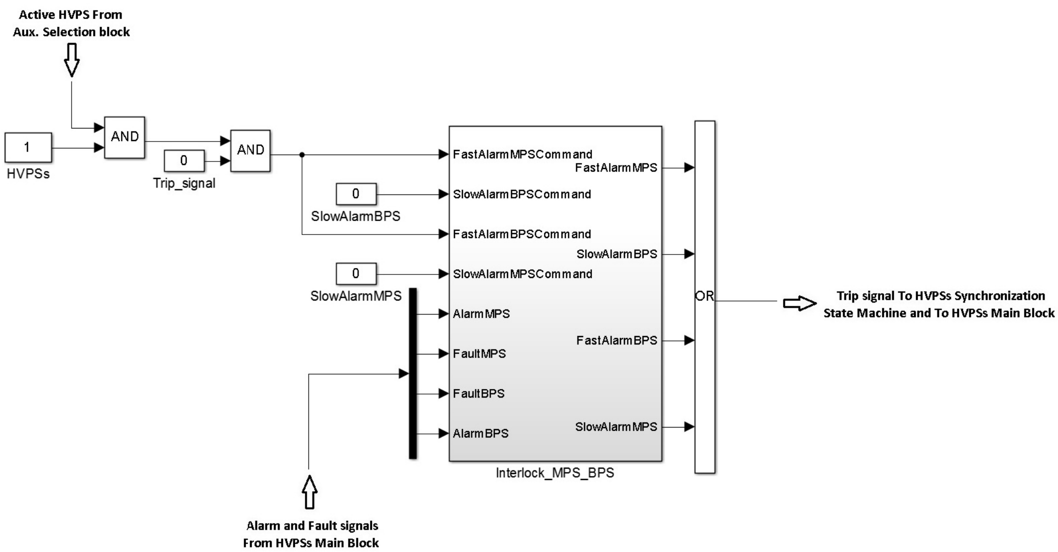

Figure 4.11: Model of the HVPSs Interlock System.
Source: MATLAB/SIMULINK

This system has two different trip signals: Faults and Alarms that can be either Fast or Slow, depending on how important the failure is. For the time being, for safety reasons, it has been decided that any of these fault or alarm signals will be treated at the maximum importance level in order to perform a fast actuation to trip the system. This is done with the 'OR' door outside the block, which makes that any of these different kind of failures will produce the same actuation method, sending a trip signal to both the HVPSs Synchronization state machine and to the HVPSs Main Block. Internally, this system works as follows.

In Figure 4.11, the trip signal from the Main State Machine is combined with the Active/Inactive selection of the HVPSs. If the user decides that the HVPSs will not be used in the simulation (HVPSs Constant block set to '0'), the trip signal will have no effect on the Interlock system.

Figure 4.12: Model of the Interlock System internal operation.
Source: MATLAB/SIMULINK

It is important to mention that this Interlock system is incomplete: the trip signal will come from a higher level state machine that will be implemented in the future to the model. For the time being it has been decided to have it by a Constant block that can be modified by the operator so that the system is already there for when the higher level machine will be added.

4.4.3 HVPSs Synchronization

When all the auxiliaries are working in steady state and both HVPSs are in Idle state, the Start HVPSs state machine sends the *Start* signal to the HVPSs Synchronization state machine. When the HVPSs have to be turned ON/OFF, it is essential to do it following a certain sequence. For the operation of the gyrotron, when turning on, the MPS has to be turned on first and, once the voltage applied reaches a certain threshold, then the BPS can be started. The turning off sequence is exactly the opposite: the BPS has to be turned off first and, once the output voltage is below a certain threshold, then the MPS is stopped. When the turning off signal appears, the voltage of the BPS starts decreasing. Once the voltage of the BPS is below the threshold (the voltage signal of the BPS is then off), then the MPS voltage starts ramping down.

This threshold crossing is indicated by the *MPS_ON* and *BPS_ON* input signals in Figure 4.13, coming from the HVPSs Main Block.

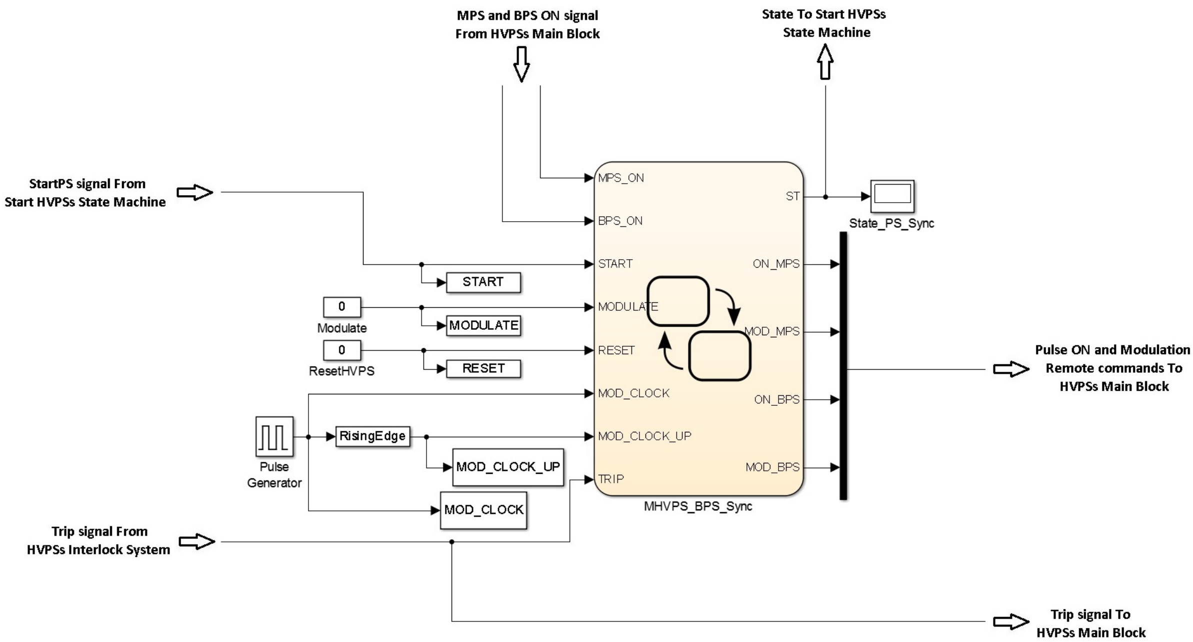

Figure 4.13: Model of the HVPSs Synchronization state machine.
Source: MATLAB/SIMULINK

The gyrotron can operate in two modes: in continuous pulse, used for example for global heating of the plasma (among other uses) or in modulation mode, which, in ITER, will be used to control the formation of islands inside the plasma (magnetic lines that close on themselves locally, destabilizing the plasma) and destroy them when they appear. For the Test Facility testing, there will not be any plasma to work with so this modulation will be done following a reference fixed by the Pulse Generator (on the left side in Figure 4.13). There is also a reset input in case of having a fault in the system.

The synchronization of the MPS and BPS can be seen in the state machine in Figure 4.14.

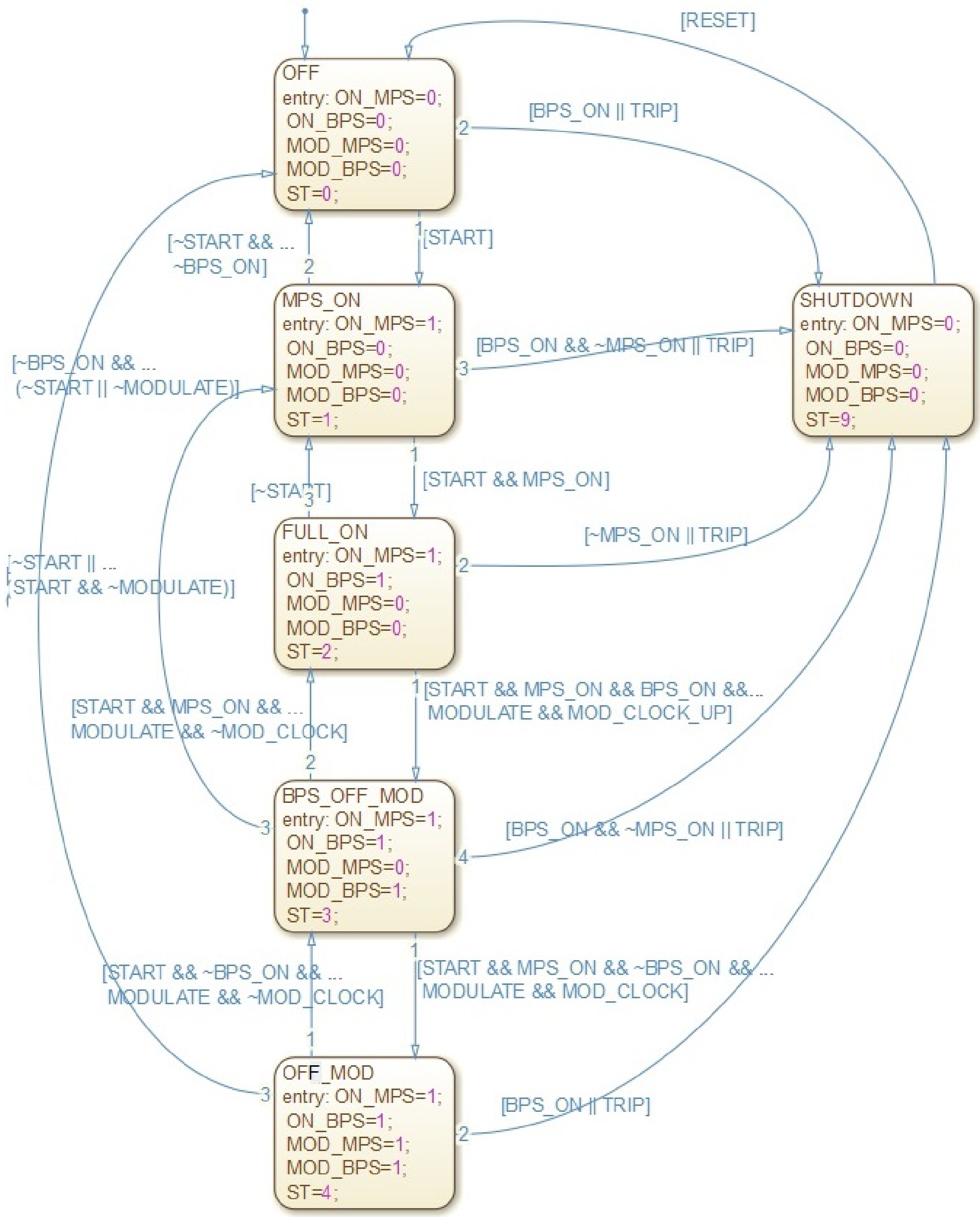

Figure 4.14: HVPSs Synchronization state machine.
Source: MATLAB/Simulink

Once the Start HVPSs state machine sends the *Start* signal, the MPS is turned on. Once the MPS voltage reaches the fixed threshold, the *MPS_ON* input signal becomes '1' and the state machine moves to the FULL_ON state, where the BPS is turned on as well.

If the gyrotron is working in modulation mode (*MODULATE* is '1'), when a rising edge appears in the Pulse Generator signal, the state machine will move from FULL_ON to BPS_OFF_MOD. In this state, the voltage of the BPS will start decreasing. Once the BPS goes below the fixed threshold, the *BPS_ON* input signal will go from '1' to '0' and, if the reference signal is at high level, the system moves to OFF_MOD, where the voltage of the MPS will start decreasing, until the reference signal (Pulse Generator from Figure 4.13) falls to low level, going back to BPS_OFF_MOD state. At this point, the MPS current will start increasing again and, once it crosses its threshold, MPS_ON will go back to '1', sending the state machine back to the FULL_ON state, where the voltage of the BPS will start increasing again.

If at any moment during the operation of the HVPSs there is a trip signal or any unexpected behaviour, the state machine will directly move to the SHUTDOWN state where both HVPSs outputs are turned off.

4.4.4 HVPSs Main Block

The HVPSs Main Block is the part of the HVPS system that contains the model of the power supplies. Both power supplies can be operated locally or remotely, which is why there are two sets of commands. The use of the local or remote interface depends on the LOC/REM switches that both the MPS and the BPS have. If one mode is chosen, the commands of the other one will have no effect at all on the power supply.

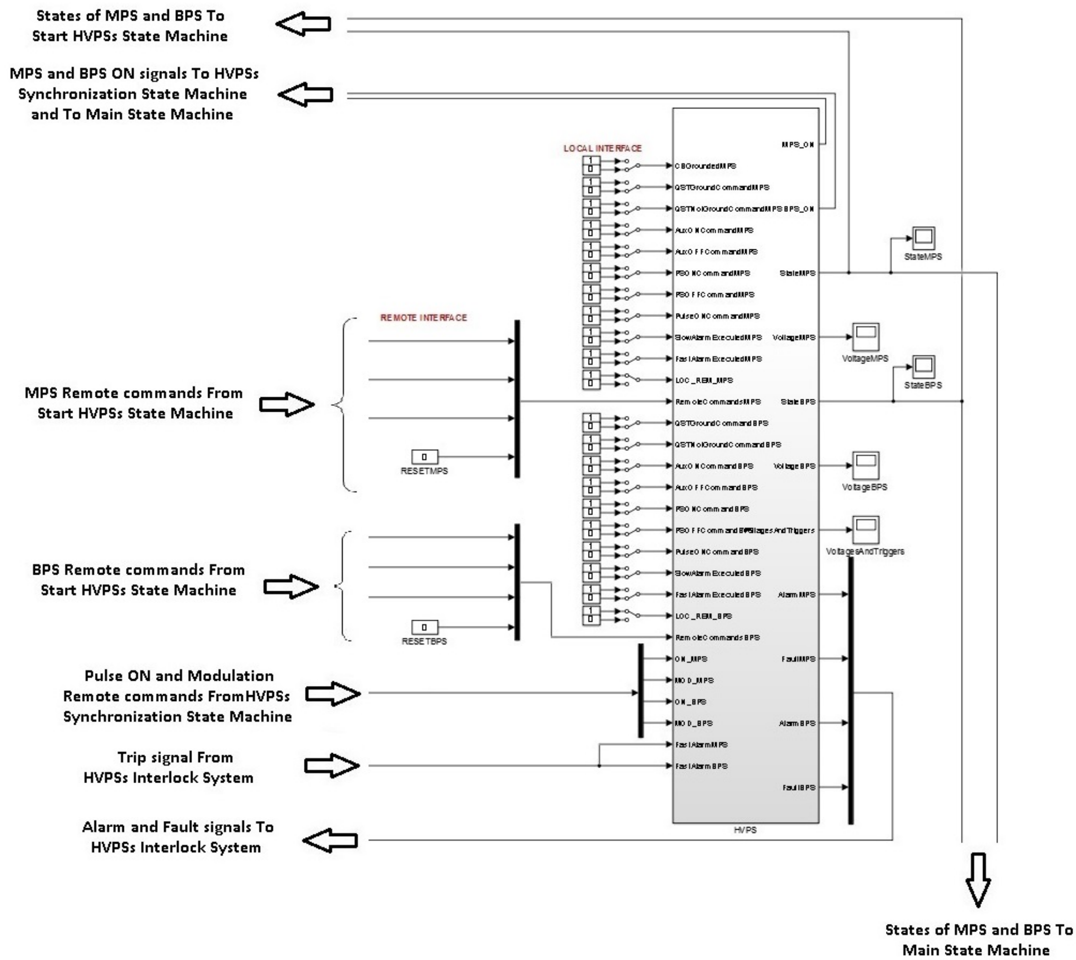

Figure 4.15: Model of the HVPSs Main Block.
Source: MATLAB/Simulink

As it can be seen in Figure 4.15, the HVPSs Main Block receives input signals from the local interface plus the ones coming from all the previously described systems that are part of the HVPSs Remote control:

- The Start HVPSs state machine sends a whole set of remote commands to both the MPS and the BPS to initialize them.
- The HVPSs Synchronization state machine is the one in charge of turning on/off the output power and activate or not the modulation mode.
- The HVPSs Interlock System is in charge of sending the Alarm signals to both PSs.

In response to these different input signals, the HVPSs Main Block provides different outputs:

- The states of the MPS and BPS, which are extracted from their state machines. These signals are sent as inputs both to the Start HVPSs state machine, which, as explained before, evolves depending on the HVPSs state, and to the Main State Machine, to generate the *HVPSOK* signal.
- The MPS and BPS ON signals, indicating if the power supplies voltages are above or below the fixed threshold. These two signals are sent to the HVPSs Synchronization state machine, in order to control the ON/OFF sequence and to the Main State Machine, forming the *HVPSOFF* signal.
- The voltages of both power supplies, which can be observed in the scopes that are connected to the outputs.
- The Fault and Alarm signals generated in the power supplies, which are sent to the HVPSs Interlock System in case it is necessary to generate a trip signal.

Inside the HVPSs Main Block, the state machines of the MPS and BPS can be found as well as the voltage generation blocks, which take into account different factors:

- The state of the power supply: if the PS enters the steady state (ST = 100), then the voltage starts increasing progressively towards the reference; if there is an Alarm (ST = 200 for MPS and BPS), the voltage starts decreasing slowly until reaching zero or; if there is a Fault (ST = 300 for MPS and BPS), the voltage drops quickly to zero (see *Appendix A*)
- The modulation signal coming from the HVPSs Synchronization state machine.
- The voltage threshold that determines when the power supply is considered as being ON or OFF.

The model of what has just been explained can be seen in Figures 4.16, 4.18 and 4.17 for the MPS, the BPS and the voltage generation model respectively.

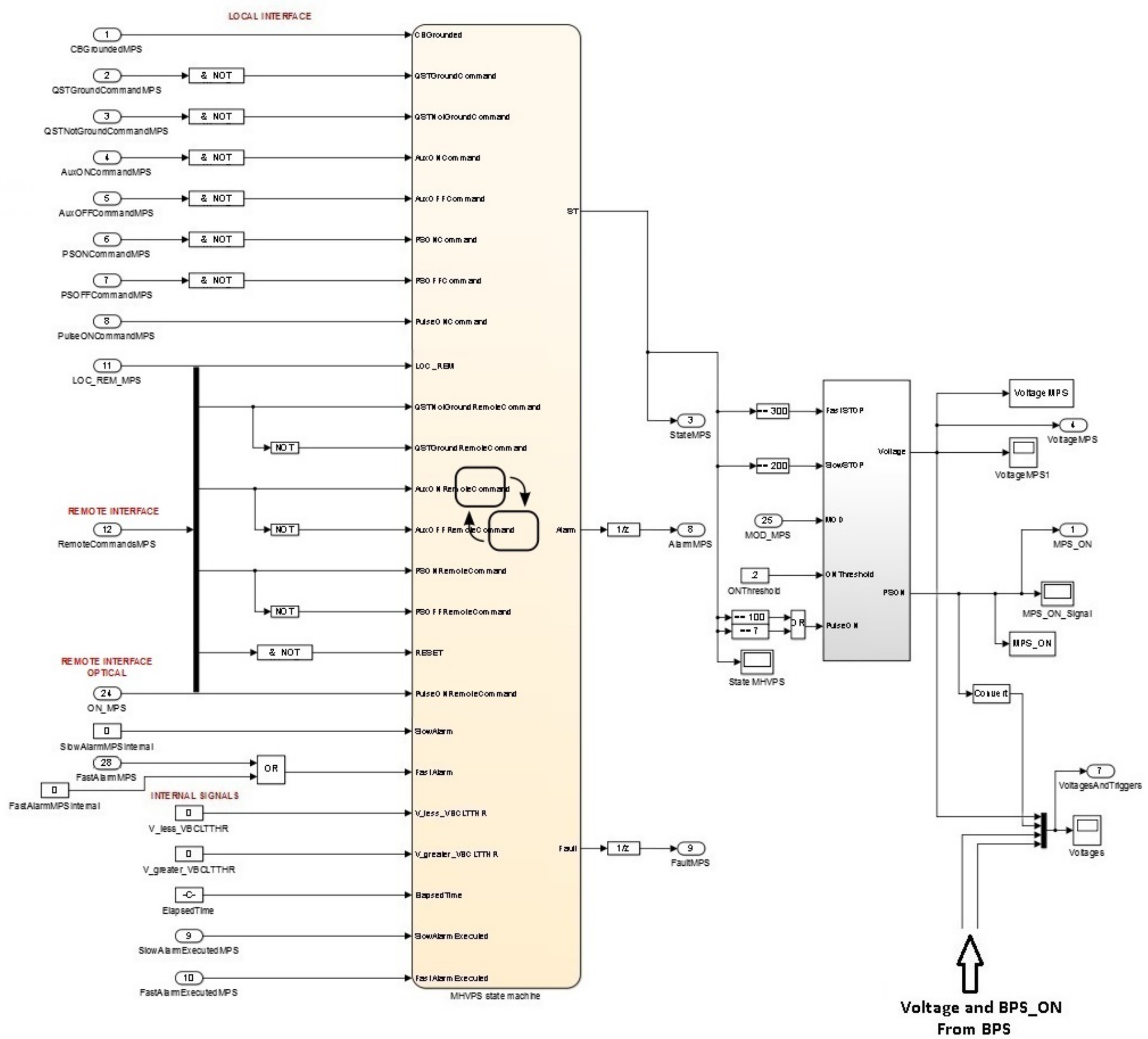

Figure 4.16: MPS state machine and voltage evolution.
Source: MATLAB/Simulink

The voltage generation block operation is based on determining the voltage slope depending on the state of the MPS. It has the following structure:

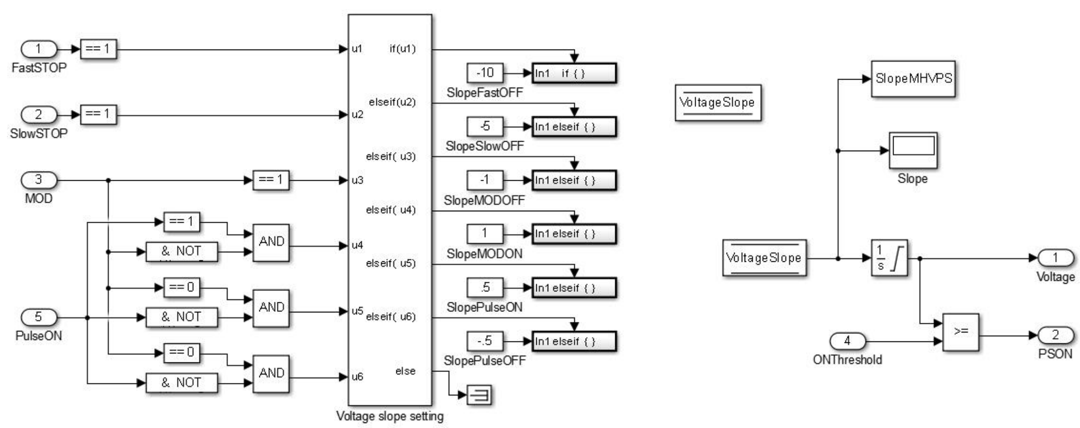

Figure 4.17: Model of the MPS voltage generation block.
Source: MATLAB/Simulink

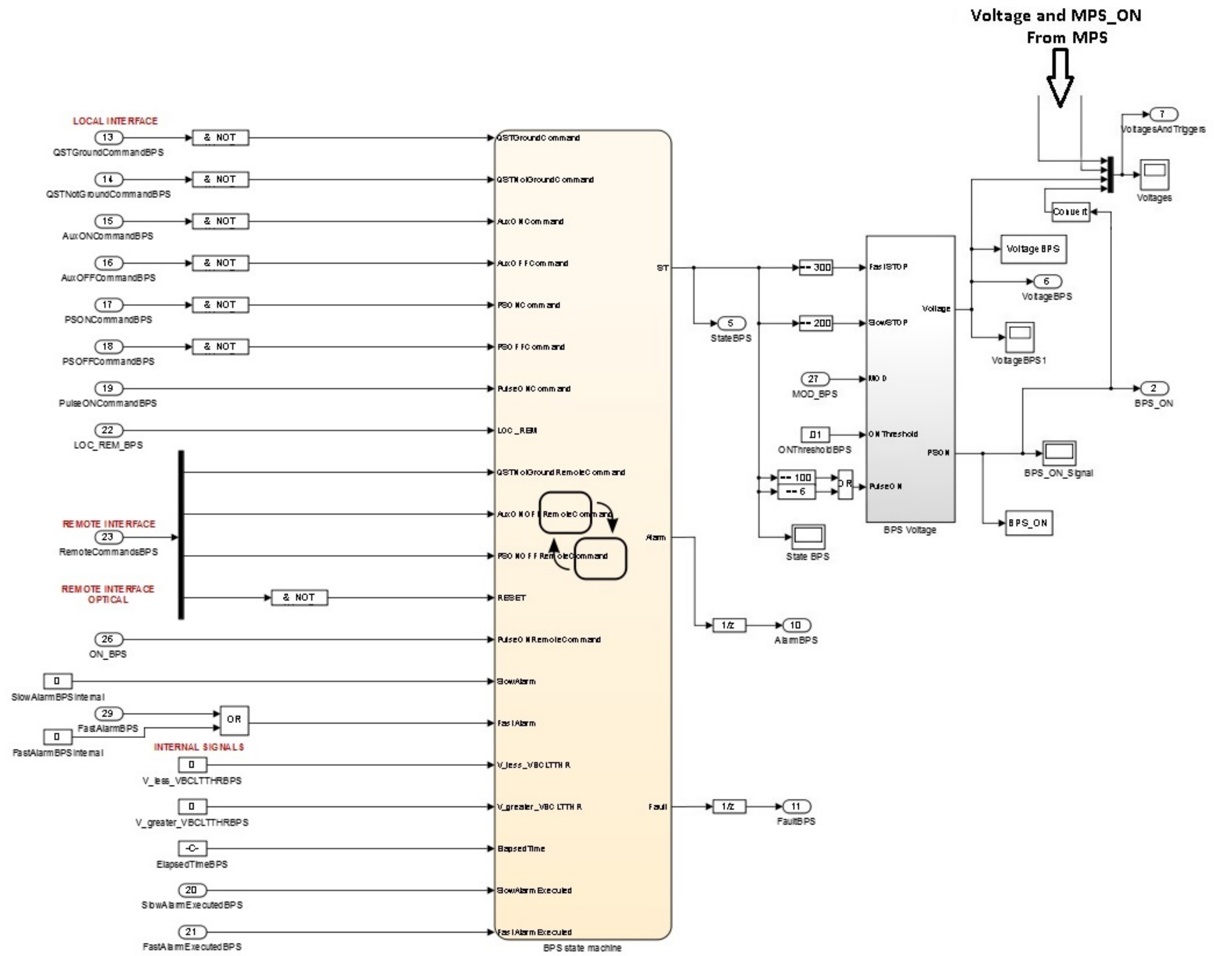

Figure 4.18: BPS state machine and voltage evolution.
Source: MATLAB/Simulink

About Figure 4.17; the *Voltage Slope* setting is a condition block that, depending on the state of the MPS and on the modulation signal value, fixes the voltage slope to follow for ramping up or down. In normal operation and no modulation mode, when turning on the MPS (*PulseON* goes from '0' to '1'), the voltage slope is fixed at 0.5 (condition *u5*). The voltage slope is stored in the variable *VoltageSlope* and then used in the right part to generate the voltage: the voltage slope is integrated through time (generating the output current signal) and, once it becomes bigger than the *ONThreshold* (fixed at 0.2 for the MPS), the *PSON* (or *MPS_ON*) signal becomes '1'.

For the turning off (in normal conditions, with no alarms or faults), the *PulseON* signal goes from '1' to '0', so the voltage slope becomes -0.5 (condition *u6*). This will happen after the BPS voltage is below the threshold. For this case, the voltage starts decreasing.

The Voltage Slope is different depending on each situation: in case of fast stop request, the slope is -10. For the modulation mode, the voltage slopes are +/- 1.

The Voltage generation for the BPS is exactly the same as the one of the MPS. The BPS voltage will start ramping up when the MPS voltage reaches the ON threshold. This is controlled by the HVPSs Synchronization state machine, which will not send the PulseON signal to the BPS until the *MPS_ON* signal becomes '1' (see Figure 4.14). The only difference between the MPS and the BPS voltage generation is the *ONThreshold*, which is fixed at 0.01 for the BPS. This is done for safety reasons as, for the OFF sequence, it is essential that the voltage of the BPS is very close to zero before turning off the MPS.

Chapter 5

HMI Integration into the Model

The SIMULINK model that has been described previously is big and contains many subsystems, which means that it is not a user-friendly environment to interact with during a simulation. It would be useful to be able to act on the simulation and having a way of displaying the most important parameters and information from the model in a simple and compact way. The main actions that can be done on the system that the user should be able to control are the following:

- Start / Pause / Stop the simulation.
- Fix the simulation time.
- Start / Stop the different sets of auxiliaries to start running the whole system.
- Select the active components for the simulation.
- Inject faults in different parts of the system to see how it will react.
- Reset all the systems and subsystems to restart the operation after solving a fault.
- Decide if using the normal or the modulation mode of the HVPSs.
- Have the possibility to change some of the system's internal parameters.
- Decide if the simulation will be a short or a long pulse (to use the appropriate cooling).
- Fix if the HVPSs will be operated in Local or Remote mode.
- Be able to operate some necessary switches for the Remote control.

Another essential part for the user is being able to see what is happening during the simulation to follow its evolution. The information that should be easily displayed is the following:

- The state of the Main State Machine, to know if the sequence if being followed correctly and know the state of the whole system.
- The state of each of the auxiliaries at every moment, in order to see if they are operating correctly and behaving as they should.
- The state of the HVPSs.
- The execution time of the simulation.

For this purpose, different interconnected HMIs (Human-Machine Interfaces) models have been built with different features and settings using the *GUI* (Graphic User Interface [17]) functionality of MATLAB.

5.1 Design and content of each HMI

5.1.1 Main HMI

The main HMI is responsible of displaying the states of all the auxiliary systems, the HVPSs and the Main State Machine; starting / pausing / stopping the simulation and others. All the other auxiliary HMIs are accessible through this central one. To see its structure and features distribution, see Figure 5.1.

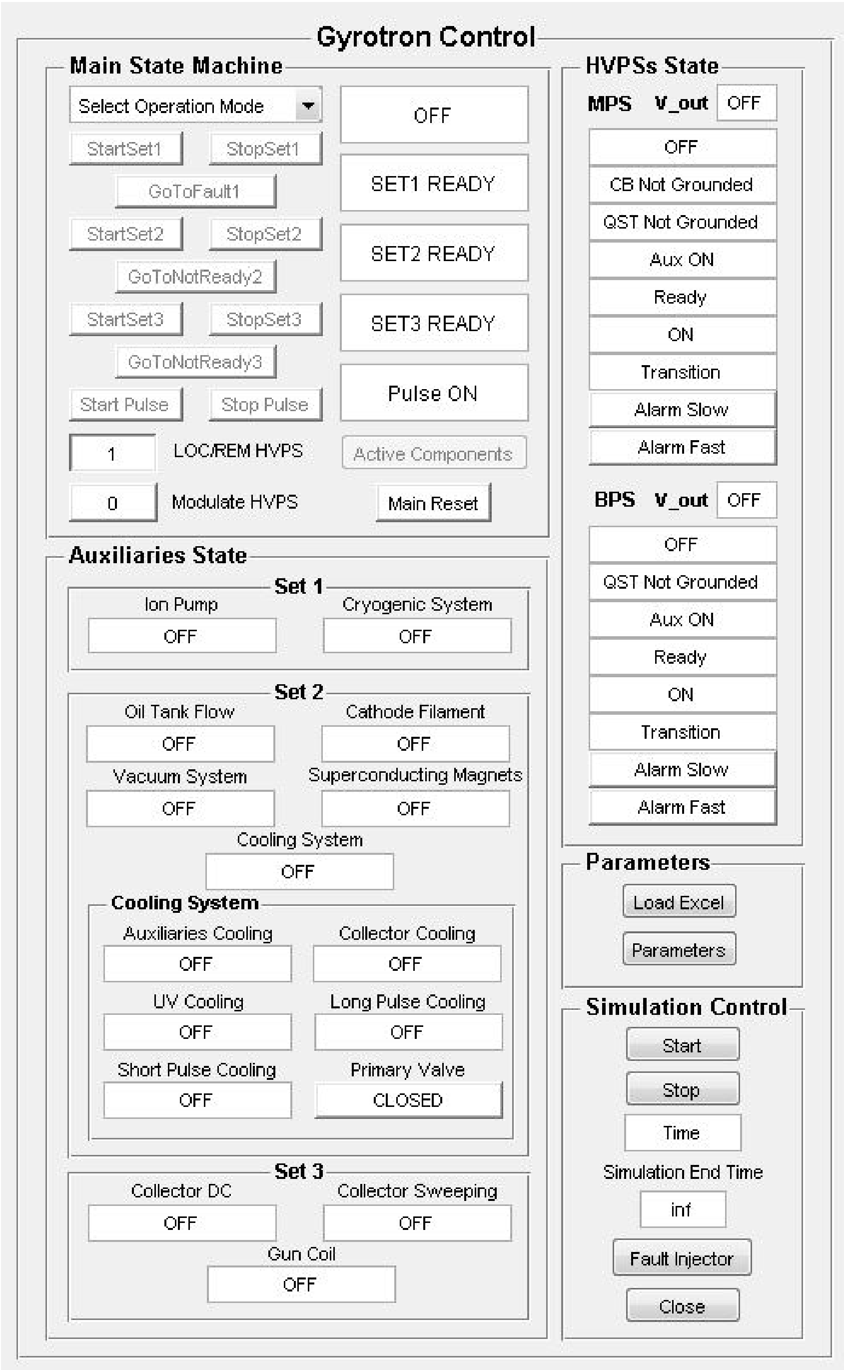

Figure 5.1: Main FALCON Control HMI.
Source: MATLAB/GUI

The HMI is divided into five panels:

- The control of the **Main State Machine** and the modes of operation of the gyrotron. There is also a pushbutton (*Active Auxiliaries*) that allows opening another HMI (see Figure 5.2) in charge of selecting the active components for the simulation when operating in test mode (Auxiliaries and HVPSs).
- The **Auxiliaries State**, where the state of all the auxiliary systems, organized by sets, is displayed as the simulation evolves. There is a subgroup for the Cooling System that is composed of several circuits. The Primary Valve can be actuated (closed or opened) from this HMI using the pushbutton.
- The **HVPSs State** panel, where all the different states of the MPS and the BPS as well as the output voltage ON signals (*MPS_ON* and *BPS_ON*, next to the *V_out* text) are displayed. Both have some states represented as buttons (*Alarm Slow* and *Alarm Fast* for MPS and for BPS). This is because they can be actuated: in case of having an Alarm (Fast or Slow), if the alarm has been executed and solved, the corresponding pushbutton can be pressed and then the block will indicate *'Alarm Solved'*. Then, if all the faults of the model are solved, it will only be necessary to press the *Main Reset* button to restart the operation of the system.
- The **Parameters** panel, where the parameters that are located in different parts of the simulator can be loaded and modified. The default parameters are all stored in an *Excel* file named *'References.xlsx'*. By pressing the *Load Excel* button, the program will automatically read the file and import all those parameters in the workspace. If the parameters are not loaded, the simulator cannot work. The *Parameters* button opens another HMI (see Figure 5.3) where all the different parameters from the *Excel* file are included and can be directly modified by the user. By pressing the *Parameters* button, the value of all the parameters from the file are directly imported as well (even if the *Load Excel* has not been pressed). Pressing the *Load Excel* is a faster way of loading all the parameters if the user does not need to check or modify any of them.
- The **Simulation Control** panel, which allows starting, pausing or stopping the simulation. It also displays the execution time of the simulation and allows changing the simulation duration (fixed to infinity by default). It also has the *Fault Injector* button that opens a last HMI (see Figure 5.4) that can insert faults in different parts of the system. The HMI closing button is also located in this panel.

All these panels are dynamic: buttons can be pressed, parameters can be modified, 1/0 settings can be changed and the displays are constantly updated to show the information in real time.

To make it more visual, these displays also have colors depending on the state in which the concerned system is:

- In the Main State Machine and HVPSs State panels, the green color represents the current state in which the state machine is. The rest will have the default white background color.
- In the Auxiliaries State panel, when the Aux. is OFF, the block is white, when it is being started it becomes blue and when it is in normal operation state it turns to green.
- In the HVPSs State panels, when the ON signal of the power supply is '1', the display shows an *'ON'* with blue background. When it is OFF, it keeps the default white color.
- For all of the panels, red is used for faults and orange for solved faults (waiting for the reset signal).

5.1.2 Auxiliaries Selection HMI

As it has been mentioned in the previous chapter, for the *Auxiliary testing* mode (and only for this mode), all the different components of the simulator can be defined as Active or Inactive by the user. This is why there is a secondary HMI that allows picking which systems will be used in the simulation. If the pushbutton displays a '1', the component is active; if the pushbutton is a '0', the component is inactive. This will affect all the auxiliaries and the HVPSs changing automatically the values inside the Constant blocks that can be found both in the global model and inside the *AuxiliaryPS* block. There is a footnote included in the HMI to remind the user that, when operating in testing mode, the Cathode Filament and the HVPSs cannot be operated at the same time. If the user tries to start the simulation keeping both systems active, the main HMI will display an error message with this same information .

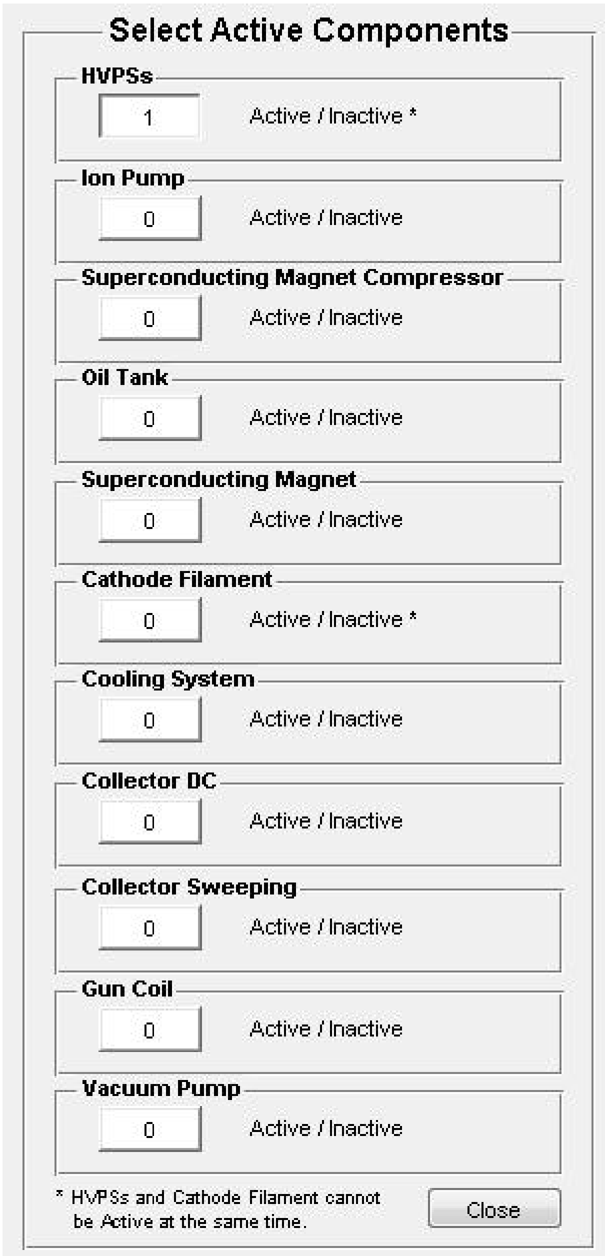

Figure 5.2: Select Active Components HMI.
Source: MATLAB/GUI

5.1.3 Parameters Setting HMI

The simulation model contains several parameters in different subsystems, which are all contained in the *Parameters* HMI (see Figure 5.3). Some of these parameters are characteristic of the different power supplies and others are reference values that need to be fixed by the operator.

The characteristic parameters are the transfer functions of the different power supplies, which depend on the power supply's type, size, power, etc. These values are fixed and cannot be changed by the operator. However, for the operation of the simulator, it has been considered useful to allow modifying these parameters in order to affect the simulation time (depending on the transfer function, a signal can take longer or shorter time to reach the reference value). This allows accelerating the simulation when needed.

The reference values are the target values for the power supplies. In this system there are three main types of references:

- Output current reference (for most of the auxiliaries), expressed in amperes (A), fixing the desired current output of the power supply for the correct operation of the auxiliary inside the system. This reference value has to be set before starting the simulation. However, for some auxiliaries like the Superconducting Magnets PS, the Filament PS and the Gun Coil PS this reference value can be modified during the simulation to adapt it to the needs of the system. This is done by setting the new target value in the *'New Reference'* block and then pressing the *'Enable new Reference'* pushbutton, which will operate a switch that will change from the old reference to the new one. This new reference can be modified again by modifying this time the *'Current Reference'* block value and pushing again the button to switch from one reference to another. The active reference value is the one displayed in red.

- Mass flow reference (for the cooling subsystems), fixing the necessary flow that the pumps of each circuit of the cooling system need to reach. These mass flows are expressed in liters per minute (L/min). The values need to be fixed at the beginning of the simulation.

- The current sweeping power supply needs a rise and fall time in order to fix a saw-shaped current reference for the sweeping, expressed in seconds (s). This will directly affect the heat load distribution on the walls of the collector.

It is in this HMI where the user has to decide if the simulation performed will be a short or a long pulse, as this will affect the necessary cooling for the dummy load. Depending on the length of the pulse, the cooling system will use one pump or another for the cooling of the load.

As mentioned previously, all these parameters are also stored in an *Excel* file called *'References.xlsx'*. By pressing the *Reset Parameters* button, all the parameters take the default values stored in that file.

For the Superconducting Magnets PS, there is an additional parameter to fix: in order to reach the steady state conditions, the current output has to reach a stability point, considered as being inside a certain error margin around the reference value (+/- 1% error margin has been used for the model). In order to make sure that the whole signal is inside that margin, the best thing is testing different points of the current curve. The *'Samples per T/2'* textbox represents the number of testing points in half period of the signal in the simulation. The more points there are, the more accurate the checking will be.

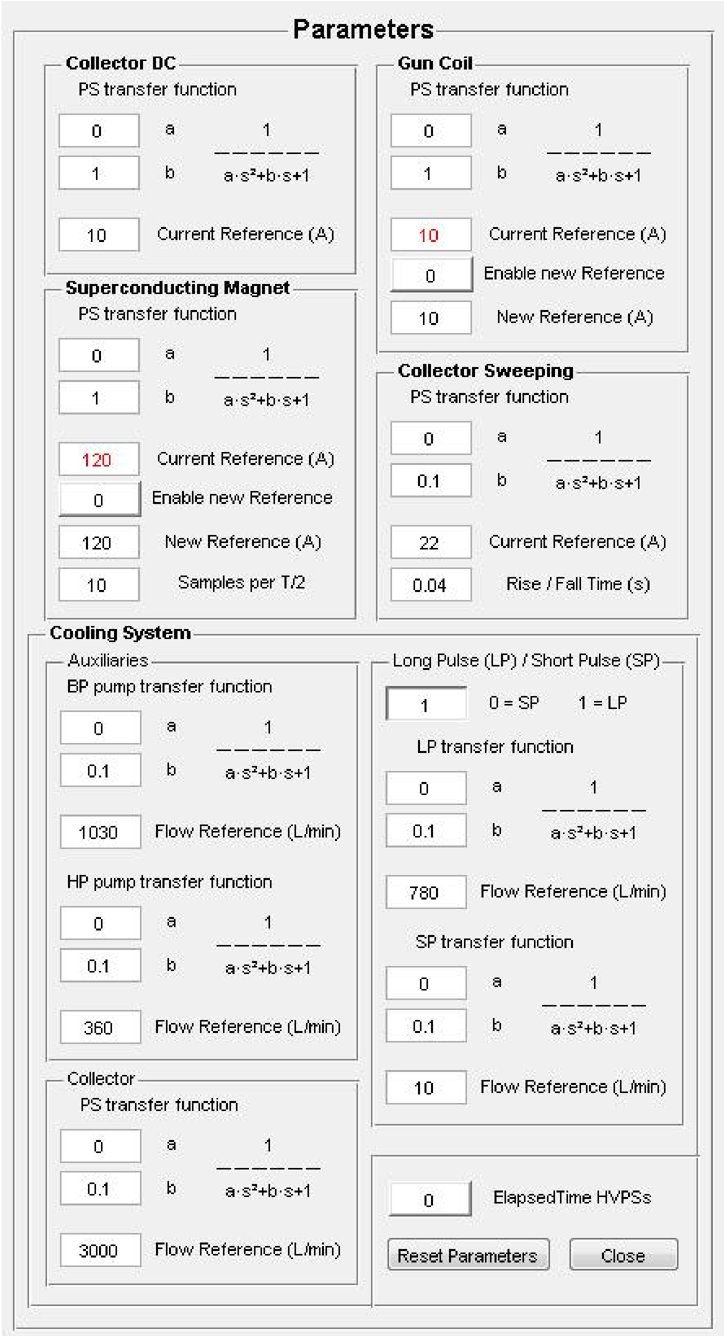

Figure 5.3: Parameters Setting HMI.
Source: MATLAB/GUI

5.1.4 Fault Injector HMI

The last HMI is the one in charge of injecting faults inside the system. Most of the auxiliary systems, as well as the HVPSs, can have internal or external faults. The *Fault Injector* HMI allows generating fault signals in each of these subsystems by means of pushbuttons. When the button is pressed, displaying a '1', a fault is generated in the corresponding subsystem. If the button is pressed again, going back to '0', the fault is cleared.

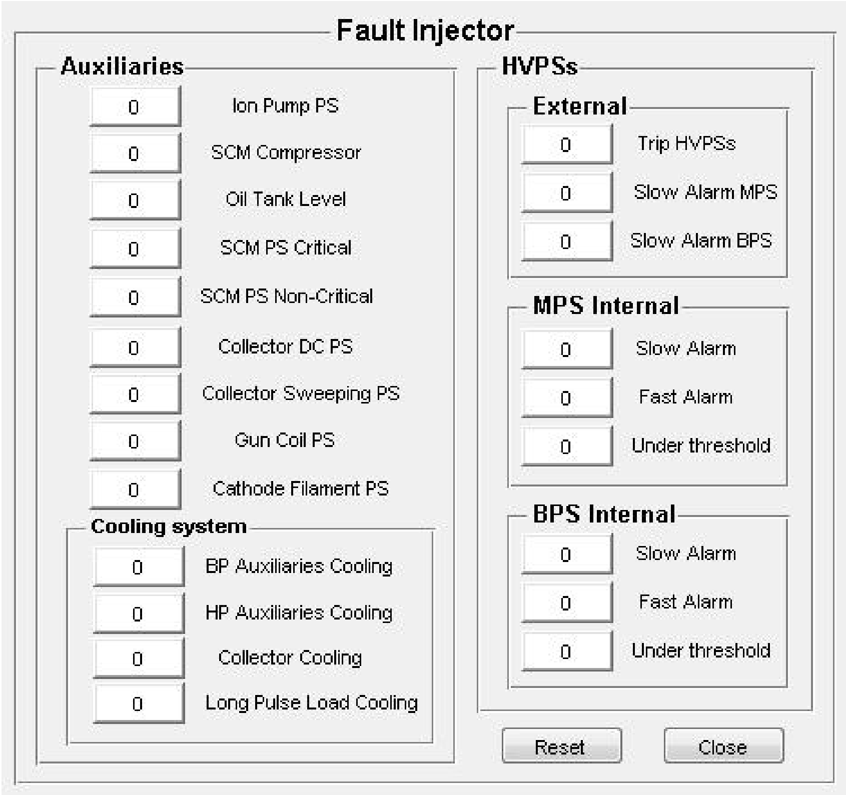

Figure 5.4: Fault Injector HMI.
Source: MATLAB/GUI

The faults related to the auxiliaries are Constant blocks inside each of the subsystems modelling each auxiliary that can be seen in Figure 4.6 (or Figure 4.7 for the cooling subsystems). For the HVPSs, the external faults are linked to blocks that can be seen in Figure 4.11 and the internal ones in Figures 4.16 and 4.18 for the MPS and the BPS respectively.

Some of the auxiliaries could have their own model of random fault generation and fault solving systems but, in order to give full control of the simulator to the user, these internal systems have been removed so that faults can only be inserted and removed through this HMI or by directly modifying the fault input block value inside each subsystem.

5.2 Simulations and Validation of the model

All along the process, the documentation of each subsystem and the requirements on the operation of the gyrotron system have been read and checked over and over. The content of the datasheets from all the power supplies have been fully integrated inside the model, taking into account all the possible signals and faults that each of the subsystems could have.

In order to decide the way how the whole system was coordinated, several meeting with the rest of the members of the department took place. These meetings allowed splitting all the auxiliaries in the three sets described and the stage process of making the HVPSs progress step by step through their state machines at the same time the different sets were activated.

Before integrating the final model of each auxiliary, a very simple ON/OFF state machine was implemented. All of them were replaced one after the other by the real models, testing the global model every time an auxiliary was modified to adapt it to the new conditions, the new signals and the new possible faults.

During the whole process of development of both the model and the HMIs, simulations were run to make sure that the whole system was behaving in the expected and required way.

In this report there are two examples of simulations that have been run with the final model and HMIs:

- **First simulation**: In consist in a pulse, going from OFF state to PULSEON on the Main State Machine with a fault in the SCM PS.
  - First the system evolves progressively from OFF to PULSEON with all the necessary commands in the middle
  - During the pulse, a fault is injected in the SCM PS subsystem (the SCM PS belongs to set 2). The Main State Machine should reach the SET2NOTREADY state.
  - After some time, the fault is solved and a main reset is done to the system. The Main State Machine should stay in the same state but the SCM PS should start going back to normal operation again.
  - Then, it is decided to stop the second set, in order to check in a more accurate way the reason of the fault and the integrity of the SCM PS. The system should then move to StoppingSet2 and finally to SET1READY (when all components from the second set are off).

  The graph showing the evolution of the voltage in both HVPSs will be shown in order to see that after the fault, the HVPSs voltage start decreasing progressively (first the BPS and then the MPS) towards zero.

- **Second simulation**: During a pulse, a trip signal is sent to the HVPSs.
  - When receiving the Trip signal, the voltage of the HVPSs should drop extremely fast in order to protect the power supplies and the gyrotron. Both the MPS and the BPS should move to Fast Alarm state.
  - After some time, the Trip signal is cleared and the Fast Alarm protocols are executed first for the MPS and then for the BPS. Both state machines should then move to Fast Alarm Solved.
  - Once the alarms have been solved, a reset is done on the whole system. From the Trip signal, the Main State Machine should have moved from PULSEON to SET2NOTREADY (corresponding to faults in the HVPSs). It will stay there until the operator decides if starting or stopping the second set.

  The graph showing the evolution of the voltage in both HVPSs will be shown and studied to make sure that the fast shutdown has been done.

Both simulations can be found in *Appendix B.1* (for Simulation 1) and *Appendix B.2* (for Simulation 2).

A part from that, it was decided that it would be useful to have a code that could run tests on the model automatically using the input sequence that the user wants to test.

This would mean that there would be no need of pressing any button for starting the different set or the pulse, the code would follow step by step the sequence of states given by the user and would send the required commands depending on the next target state.

This code would be very useful for future modifications of the model to check that the global system keeps working correctly.

The code for that purpose, created on MATLAB, provides two output values:

- The sequence of states followed by the model in the form of a list (these states correspond to the ones from the Main State Machine)
- A parameter that checks if the sequence given at the input by the user and the sequence obtained using the code are the same (the value is '1' if both sequences match and '0' if they don't)

The option of adding faults in the sequence is also available by writing the name of the system in which the fault is injected in the sequence. It is important to mention that the user needs to know perfectly the structure and number of the states of the Main State Machine as, after injecting a fault, the code requires the user to put the number of the fault state where the system is supposed to go (30 for FAULTSET1, 31 for SET2NOTREADY or 32 for SET3NOTREADY). If the sequence continues after injecting the fault and reaching the right fault state, then the code will automatically clear the fault and reset the system in order to proceed to the following state requested in the input.

If there is an error in the sequence given by the user, the program will stay stuck in an infinite loop trying to get to a state that cannot be reached from its current status.

This code can be seen in *Appendix C*.

Chapter 6

Implementation

In the end, this model is a representation of a real system with real power supplies and real components. The signals and commands described in the model need to be implemented and monitored in the real system being built and installed in Lausanne.

The FALCON system needs to take into account all the different signals coming from each of the subsystems and need to be able to send commands to all of them in order to operate them.

Before starting the installation of the different components, it is necessary to make some tests on every one of them.

From the point of view of faults, it is obvious that, as in the model, the real system will need to have *Protection Functions* that monitor the important parameters of each subsystem and can act in case of fault in any of them.

To finish, some pictures of the real components, power supplies and the control system from the Test Facility will be included to show how each of the systems looks like.

6.1 Testing and integration procedure

Before starting the integration and operation of all the different components of the gyrotron system some tests have to be performed to make sure that the different subsystems work correctly. Depending on the subsystem these tests can be exclusively focus on the electronics or on mechanical operation of components as well. These are some examples of tests performed for different auxiliaries.

6.1.1 Cooling water system

- Mechanical check of circuits:
  - Valves, load bypasses
- Check PLC wiring
  - Point to point connections
- Check PLC diagnostics
  - Hardware configuration
- Tests from local panel:

  - All flow sensors measure 0 flow and all temperature sensors measure ambient temperature
  - Digital inputs measure no fault, levels OK, flow not OK, valves closed, overpressure OK
  - Warm up temperature sensors one at a time and check variation on the PLC
  - Start UV and check status
  - Open primary valve and check flow measurements on primary circuit.
  - Switch on circuits one at a time
- Repeat tests from remote panel

6.1.2 Pumping system

- Mechanical check
- Check PLC wiring
- Check PLC diagnostics
- Tests with TIA Portal[1] directly connected to the PLC:
  - Feedback from pumps confirming pumps not active
  - Feedback from pressure sensors confirming pressure threshold not reached
  - Open/close valves and switch on/off pumps one by one
  - Control the system with the implemented state machine
- Repeat tests from remote panel

6.1.3 Filament PS

- Check PLC wiring
- Check PLC diagnostics
- Check that the correct electrical dummy load is used
- Check digital and analogue inputs
- Set current reference
- Send remote shutdown
- Test control algorithm
- Repeat from remote HMI

[1]The Totally Integrated Automation (TIA) Portal is a Siemens system that allows configuring, controlling, monitoring and acting on a digital system using different softwares

6.1.4 Gun Coil and Collector DC PS

- Check PLC wiring
- Check PLC diagnostics
- Check that the correct electrical dummy load is used
- Check digital and analogue inputs
- Set current reference
- Send remote shutdown
- Test control algorithm
- Repeat from remote HMI

6.1.5 HVPSs

- Check Modbus connection
- Put HVPS in remote mode from the local panel
- Compare list of variables in the labview program and in the PLC program
- Compare values of variables in the local HMI and in the PLC
- Send commands/configuration from the PLC and check values in the local HMI

These are just some of the tests that have been performed. Many others have been done to the rest of components like for example the gyrotron tube, which is the main component of the system.

6.2 Protection Functions

The gyrotron system needs to have protection functions that will put the system in a safe state in front of faults.

In order to show how it works, some protection functions of the different auxiliary systems have been put in a table showing, for each one of them, which are the main controlled parameters and their threshold before triggering an alarm signal. In case of having an alarm, the system has to perform a certain action in less than a given time in order to guarantee the safety and integrity of all the components.

Table 6.1: Protection functions for each system

Subsystem	Controlled Parameter	Alarm signal	Action / Time for action
Cooling water system	1. Inlet water temperature - T 2. Water flow rate - F	1. $T \geq T_{max}$ 2. $F \leq F_{min}$	Switch off HVPSs / $t \leq 50ms$
	3. Inlet water pressure - P	3. $P \geq P_{max}$	Switch off HVPSs / $t \leq 50ms$ Switch off CWS / $t \leq 1s$
SCM Cryogenic system	Cryomagnet current - I_{cryo}	1. $I_{cryo} \leq 0.99 \cdot I_{cryo\,nom}$	Switch off HVPSs / $t \leq 50ms$
		2. $I_{cryo} \geq 1.01 \cdot I_{cryo\,nom}$	Switch off HVPSs / $t \leq 50ms$ Switch off SCMCS / $t \leq 50ms$
Ion Pump PS	Ion pump current - I_p	$I_p \geq I_{p\,max}$	Switch off HVPSs / $t \leq 50ms$
Filament PS	Filament current - I_f	$I_f \geq I_{f\,max}$	Switch off HVPSs / $t \leq 50ms$ Switch off CFPS / $t \leq 50ms$ Set nominal filament value
Collector coil PS	Collector coil current - I_{cc}	1. $I_{cc} \geq 1.05 \cdot I_{cc\,nom}$ 2. $I_{cc} \leq 0.95 \cdot I_{cc\,nom}$	Switch off HVPSs / $t \leq 50ms$
Gun Coil PS	Gun coil current - I_{gc}	1. $I_{gc} \geq 1.05 \cdot I_{gc\,nom}$ 2. $I_{gc} \leq 0.95 \cdot I_{gc\,nom}$	Switch off HVPSs / $t \leq 50ms$
RF arc detector	Level of light - G	$G \geq G_{max}$	Switch off HVPSs / $t \leq 10\mu s$
MPS	1. Beam voltage - U_b 2. Beam current - I_b	1. $I_b \geq I_{b\,max}$ 2. $U_b \geq 1.01 \cdot U_{b\,nom}$ 3. $U_b \leq 0.99 \cdot U_{b\,nom}$	Switch off HVPSs / $t \leq 10\mu s$
BPS	1. Anode voltage - U_a 2. Anode current - I_a	1. $I_a \geq I_{a\,max}$ 2. $U_a \geq 1.01 \cdot U_{a\,nom}$ 3. $U_a \leq 0.99 \cdot U_{a\,nom}$	Switch off HVPSs / $t \leq 10\mu s$

As it can be seen in the Table, there are two main groups of Protection functions:

- The *Slow Protection Functions*, which need to act in the order tens of millisecond. Most of the auxiliaries (except from the Arc detector) are included in this group, as having an error or fault in any of them does have immediate consequences on the gyrotron system.

- The *Fast Protection Functions*, which need to act in the order of microseconds (more than a thousand times faster). The faults included in this category are all the ones directly related to the operation of the HVPSs and the RF Arc Detector, as having a malfunction in any of those could lead to huge damage to the whole system if the action is not immediate.

This means that there will also be two kind of controllers: a slow controller, that will monitor the states of all the auxiliaries and a fast controller, that will monitor the status of the HVPSs and the Arc Detector.

This fast controller will also be used for the synchronization of the HVPSs. It will be the one in charge of controlling the HVPSs Synchronization state machine and all the signals related to it. This is maybe not essential in case of a long pulse but it is crucial in case of using modulation, as the system needs to have a very fast response in front of the reference signal).

6.3 Real implementation in the Test Facility

During the past months, different components have been arriving from different manufacturers and countries to the Test Facility in Lausanne where they have been progressively tested, installed and integrated to the control system in order to have everything ready when the last components arrive.

The first picture shows the Main Power Supply, which consists in a huge amount of modules that are connected in series in order to be able to provide the necessary voltage. If some modules are not required they can just be disconnected. The MPS is located under the floor where the rest of the components are due to its size. This is why there are many cables going through the ceiling.

Figure 6.1: Main Power Supply Modules.
Source: Original picture from the Test Facility

The following picture shows the Local controllers of the BPS and the MPS, with the Body Power Supply at the back. The controllers have all the necessary buttons to operate the HVPSs locally, sending all the necessary commands to disconnect the ground connection, start/stop them, etc. Their state can also be monitored on the screen.

Figure 6.2: HVPSs Local Controllers and the Body Power Supply.
Source: Original picture from the Test Facility

The next picture (on the left) shows the gyrotron tube when it arrived to the Test Facility. Its size can be appreciated compared to the man standing next to it. The picture in the middle shows the gyrotron tube installed on its support and fit inside the superconducting magnets (the Jastec component). The picture on the right shows the RF output window with the CVD disk. At this point the rest of the auxiliaries still need to be installed and connected. The Cooling system channels can also be seen in the second picture.

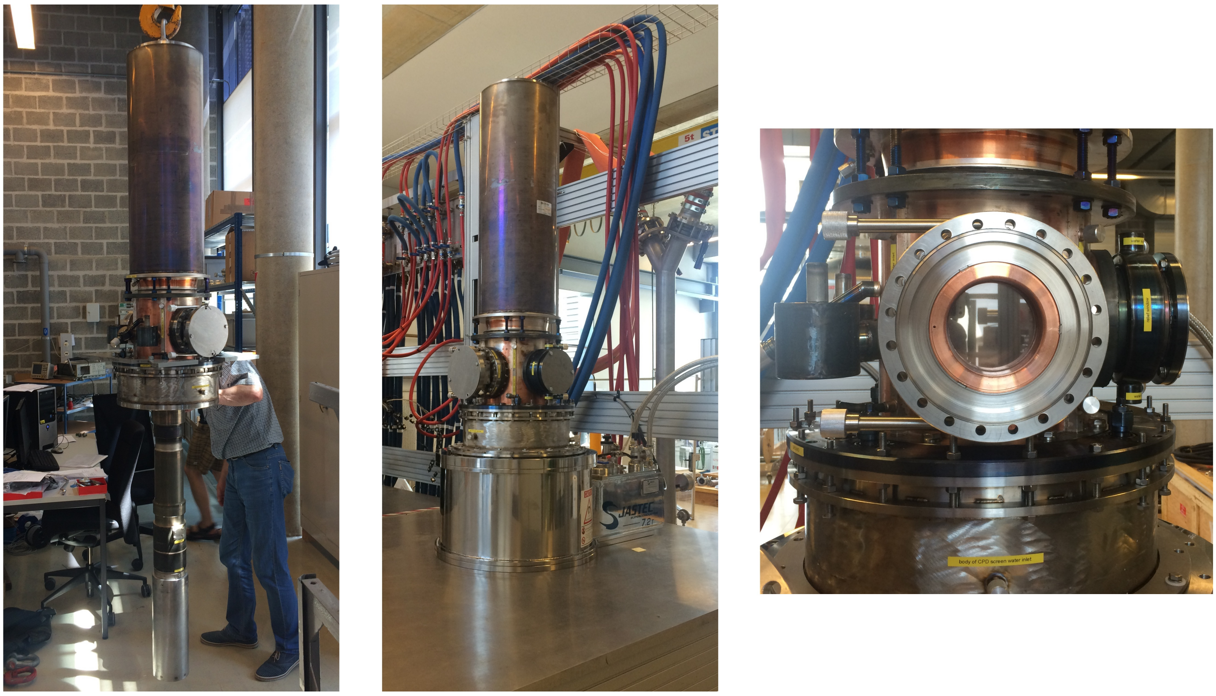

Figure 6.3: a) Gyrotron tube.
b) Gyrotron tube and SCM assembled on the support table.
c) RF output window.
Source: Original picture from the Test Facility

On the following picture, a better view of the Cooling system channels is given.

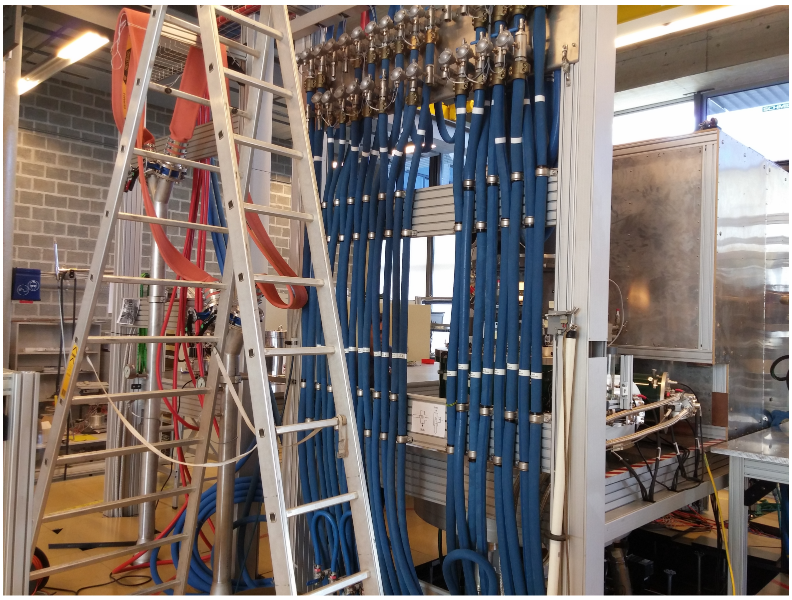

Figure 6.4: Cooling channels.
Source: Original picture from the Test Facility

The Dummy Load that will be used for the Gyrotron conditioning and the normal operation and its connection point to the MOU can be seen in the next figure:

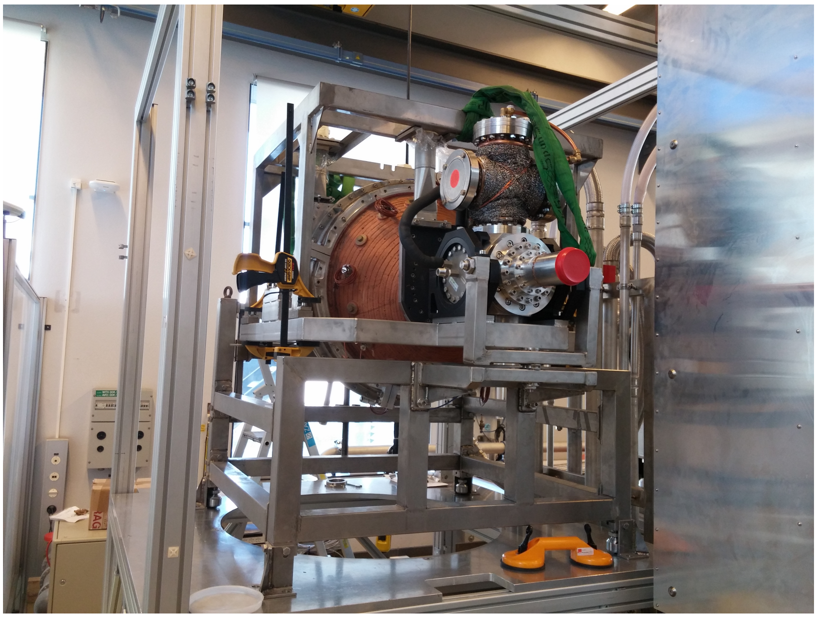

Figure 6.5: Dummy load.
Source: Original picture from the Test Facility

In the next figure there is a rack with several components.

- On the top of the rack, there is the Arc Detector controller, which measures the light intensity inside the gyrotron.
- Below the Arc Detector, there is a set of 3 devices that are in charge of synchronizing the HVPSs, acquiring and controlling their voltages:
  1. The one on the top is called the Compact-RIO, a Fast controller in charge of dealing with the fast protection functions and synchronizing the operation of the HVPSs during a pulse.
  2. The device in the middle is a server for the fast acquisition of the voltages of the HVPSs that are sent to the Compact-RIO.
  3. The last device at the bottom gets the analogue measurements directly from the HVPSs.
- At the bottom there are three different PLCs:
  1. The first one (PLC 1) is a digital I/O (input/output) system that is in charge of controlling, protecting and coordinating all the auxiliaries. It receives all the input and output signals from them and internally generates the corresponding output signals. It is in this PLC where the state machines of each of the auxiliaries is stored to check their evolution and know the output signals that need to be sent at each moment.
  2. The second one (PLC 2) is in charge of the Sweeping Fast Protection: it is important to monitor the Collector Sweeping Power Supply as, due to the large amount of magnetic fields that surround the gyrotron (coming from the different auxiliaries and the gyrotron itself), there can be an important amount of noise in the signal generated by the CSWPS. If the signal is perfectly triangular, it can happen that the heat load is not being correctly distributed on the collector walls, which can produce hot spots and then damage the gyrotron. For this reason it is important to have a good control of the sweeping signal.

3. The third one (PLC 3) is used for serial communication with the different Power Supplies, using the outputs coming from PLC 1.

All these systems (except the Arc Detector) are part of the control system of the gyrotron and have an essential role in its operation.

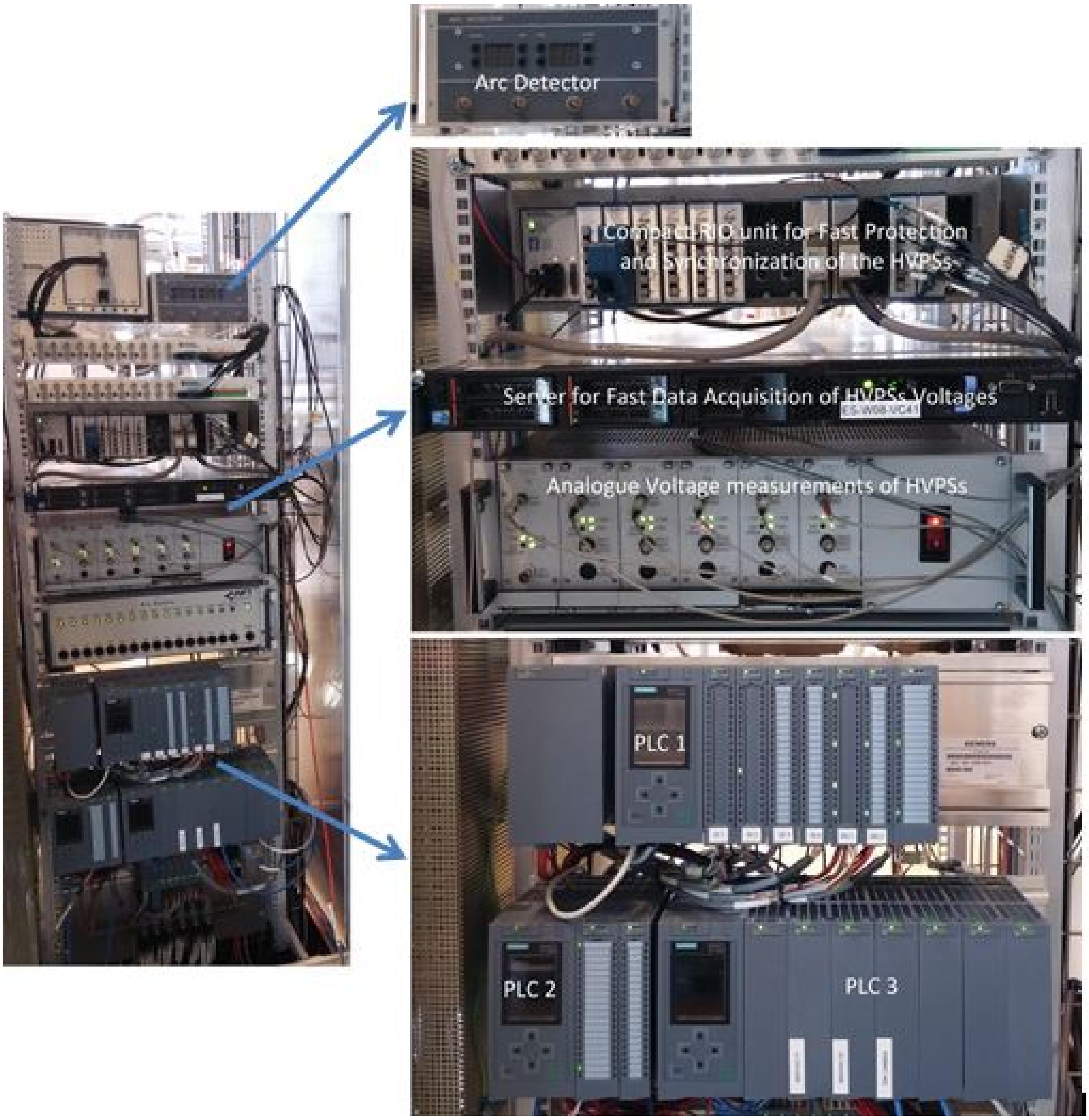

Figure 6.6: Top to down: Arc Detector, HVPSs Synchronization and Voltage Control block, set of PLCs.
Source: Original picture from the Test Facility

The next picture shows some of the power supplies that have been described in the report.

- The Gun Coil Power Supply
- The Collector DC Power Supply
- The Ion Pumps Power Supply
- The Superconducting Magnets Power Supply

Figure 6.7: Top to down: GCPS, CDCPS, CSWPS, IPPS, SCMPS.
Source: Original picture from the Test Facility

The following table shows the chronology of arrivals and testing of the different auxiliaries at the Swiss Plasma Center (SPC) Test Facility. As it can be seen, the testings on the gyrotron tube have not been performed yet as, by the time of the delivery of this project, it was just installed.

Table 6.2: Auxiliaries arrival and testing chronology

Component	Delivered at F4E	Delivered at SPC	Installed at SPC	Testing started on
Gun coil and Collector DC PS	-	15/02/2017	27/02/2017	03/04/2017
JASTEC Superconducting magnet and PS	-	05/04/2017	20/04/2017	24/04/2017
FUG Power Supply for Collector Sweeping	18/04/2017	21/04/2017	26/04/2017	08/05/2017
Gyrotron and auxiliaries by Gycom	-	29/05/2017	14/06/2017	-

This last picture shows an older gyrotron (in the middle) connected to a big metal box. Under the gyrotron, in green, there are the Superconducting Magnets. On the left, the Cooling system channels that cool the different parts of the gyrotron can be seen. The MOU is located on the right side of the picture. The MOU is not used in this case because the gyrotron is being operated in the *Gyrotron Operation on air* mode, with the RF window connected directly to the box, which is just a way of isolating the RF wave from the rest of the room. Inside the box, in front of the RF output window, there is thermal paper target that can determine the mode of the RF wave coming out of the gyrotron.

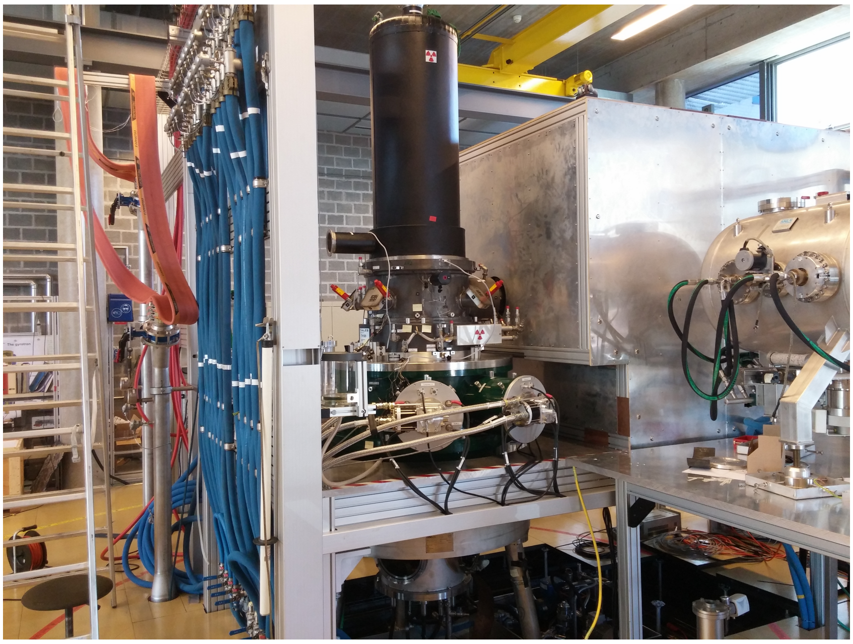

Figure 6.8: Left to right: cooling channels, gyrotron, on air pulse isolating box, MOU
Source: Original picture from the Test Facility

Chapter 7

Economic and Environmental Impact

7.1 Economic Impact

The study of the economic impact of the project has been made inside the scope of a nine months internship, considering that the supervisor has devoted an approximate amount of 2h per week solving doubts, planning, having meetings and checking the progress of the project.

This means that from the salary point of view, the cost of the project has been:

Table 7.1: Human resources cost

Concept	Cost	Units	Quantity	Cost [€]
Trainee Allowance	1 087.39	€/month	9	9 786.51
Supervisor	25.00	€/hour	72	1 800.00
			Total	**11 586.51**

All the office material and software used have also been taken into account. For the monitors, 10 years of product life time and 5 for the desktop. 10 years have also been used for the software. To calculate the amortization, 9 months of usage have been considered.

Table 7.2: Office material and software cost and amortization during internship

Concept	Original value [€]	Amortized value [€]
Dell OptiPlex 7010 desktop	736.44 [1]	110.47
Fujitsu B24T-7 LED Monitor	249.00 [1]	18.68
Dell 22” Monitor	237.60 [1]	17.82
Office Professional 2010	719.00 [1]	53.93
MATLAB		
License	2000.00 [2]	150.00
Simulink package	3000.00 [2]	225.00
Stateflow package	2850.00 [2]	213.75
TeXstudio software	0.00	0.00
MiKTeX software	0.00	0.00
	Total	**789.64**

[1] Prices provided by Fusion for Energy

[2] Prices from the official *MathWorks* website

Finally, it is also necessary to count the cost of transport to go back and forth every day to the office and the meals for lunch.

The average cost of every meal has been estimated around 7 € per day. For the public transport, the trainee was using a card with unlimited trips during three months with a special discount for families with three or more children. The cost of this card is 84 €.

Table 7.3: Transport and meals costs

Concept	**Cost per week** [€/w]	**Weeks** [w]	**Cost** [€]
Trips	7.00	36	252.00
Meals	35.00	36	1 260.00
		Total	**1 512.00**

Adding the total costs from all the previous tables, the total economic impact of the project can be obtained.

Table 7.4: Total cost of the project

Concept	**Cost** [€]
Human resources	11 586.51
Office supplies	789.64
Trips & Meals	1 512.00
Total	**13 888.15**

The estimated final cost of the project for both the trainee and the company is **13 888.15 €**.

7.2 Environmental Impact

The whole project has been based on working, reading, designing, programming and simulating a model on a computer. The result of the project is also a model that is run on a computer. This means that the project and its use do not have any impact on the environment except the consumption of light and powering the computer.

Apart from that, the public transport has been used for all the trips from the residence to the office during the whole internship. This is the most environmentally responsible way of going to the work place, minimizing the generation of CO_2. Both the residence and the office are inside the city of Barcelona, which would mean that the CO_2 emissions using private transport would have been high due to the traffic conditions when starting a finishing the working day.

The real system represented by this project, the gyrotron system in the Test Facility in Lausanne has a bigger impact as it works with many power supplies, some of them with very high power (e.g. the MPS can provide up to 4 MW of power: 50 kV of voltage and 80 A of current) and needs high water fluxes for the cooling system channels when operating:

- Cooling of auxiliaries: approximately 1400 L/min suming the flows from the low and high pressure pumps.
- Cooling of the collector: approximately 3000 L/min
- Cooling of the Dummy Load: approximately 800 L/min for Long Pulses or 10 L/min for Short Pulses.

The temperature of this water would be increased at the output after cooling the corresponding components.

However, looking at the global picture, the ITER project aims to be a solution to the energetic crisis, presenting a new, safe, sustainable and carbon-free alternative energy supply to the world. If the goals of ITER are achieved, it will have a massive impact on the energetic sector of the world, showing a new way towards a more environmentally-friendly future in the energy generation.

Conclusions and Future steps

Conclusions

Both the model and the HMI have been the result of a deep study, programming and design in order to:

- Be as close as possible to the real components, simulating the real behaviour of the power supplies.
- Take into account all the possible signals and faults from each and every subsystem to have a model as complete as possible.
- Have a visual and simple way of operating the model through the HMIs.

The objectives set at the beginning of the project have been achieved:

- The model as been presented to several persons inside Fusion for Energy and the state machines of the some of the auxiliaries have been sent to externals that are involved with the gyrotron system to check if they were correctly designed.
- The system works correctly and evolves as planned in normal operation scenarios from the starting of the auxiliaries to reaching the pulse.
- The model responds as expected in front of faults (in the auxiliaries or in the HVPSs) and is able to bring the whole system to safe conditions quickly.
- Thanks to the possibility of changing the parameters it allows accelerating some processes as bringing a power supply to normal operation that might take hours in the real component to seconds in the model, making it a comfortable, fast and easy tool to perform tests.

All the different parts of the model have been documented with different reports, all the codes have been commented so that the work that has been done can be understood and continued in the future by someone else when new elements will appear or if any modification is needed.

This is probably going to be the case as the real gyrotron system has not been tested in a pulse yet. When this process starts, some things that were not considered might come up and then some optimizations and changed might be necessary in the model to keep track of the real changes.

At the personal level, this was an amazing experience of learning how to design, program and operate a control system from zero. It also allowed the student to get involved with real systems and components; talk to different manufacturers to clarify doubts about power supplies or other electronic devices in order to know how to integrate them; work in a very nice environment surrounded by people committed to the project. Working at Fusion for Energy gives the opportunity of facing new challenges and learning new things every single day.

Being involved in such a big project as ITER, with so many different things to take into account, makes adaptability and flexibility something necessary for all the workers: when a modification in any system is done, there is another system that will be affected and will have to be adapted, which will also affect another subsystem and so forth. This is something that happened for this particular project when changes were decided to be made on some of the power supplies (in particular, the SCM PS), which required a modification of the model of the auxiliaries.

To finish, it was fascinating to be a part of such an important and big adventure as the ITER project. The nine months of internship passed incredibly fast surrounded by extremely competent professionals, experts in so many different cutting edge technology fields, always pushing a bit forward the limits of the science and engineering to face the major challenge of building this massive tokamak fusion reactor. This fascination for the project will bring me to travel to the Test Facility in Lausanne by the end of June, at my own expenses, only to see some of the last tests of the control system before the final integration of the last components and the start of the operation with real pulses.

Future steps

The model as it has been presented in this report still needs some upgrades and updates to be complete.

One of the main missing parts of the model is the integration of the Interlock System with the rest of the subsystems. The Interlock system in charge of shutting down the HVPSs in case of fault should be connected to the Main State Machine. At this step, this was not done on purpose to test the whole mode as it is before implementing higher level functions.

The Arc Detector has not been implemented in the current model as there was not a clear way to build its state machine and the signals that it works with were not totally defined either. The Arc Detector should be counted as another auxiliary system and at the same time should be directly connected to the Interlock System in order to be able to have a fast shutdown if the Arc Detector Protection function is triggered at any moment.

In the current model, the instructions only come from the user which is what is going to be used in the Test Facility. However, when the gyrotron system will be integrated inside the ITER reactor, the control system can also receive orders from the Plant Controller, which will take into account the state of the plasma by measuring several parameters and then decide if it is necessary to use more EC Resonance heating power to increase the temperature of the plasma. The EC Control System can be synchronous with the plasma pulse or not, depending on the circumstances. This means that the system that operates the gyrotron system can be different, which means that the commands can come from different origins. The model should be able to deal with this kind of things.

At the end of the month of June 2017 the last components will arrive to the Test Facility of Lausanne and the team from Fusion for Energy expect to be able to integrate them and start the first pulses by the beginning of July, with all the auxiliaries and subsystems available and ready.

Ideally, when the model is finished, it will be useful as a test platform for any kind of combination or trial before taking it to the real gyrotron system. It is an easy way to get measurements, diagnostics and predict some events that might happen.

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